Cyclotron Resonances in Electron Cloud Dynamics*

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An **Electron Cloud** is a collection of unwanted electrons in an accelerator

"Primary" electrons are generated by:

Scraping of beam particles at the wall

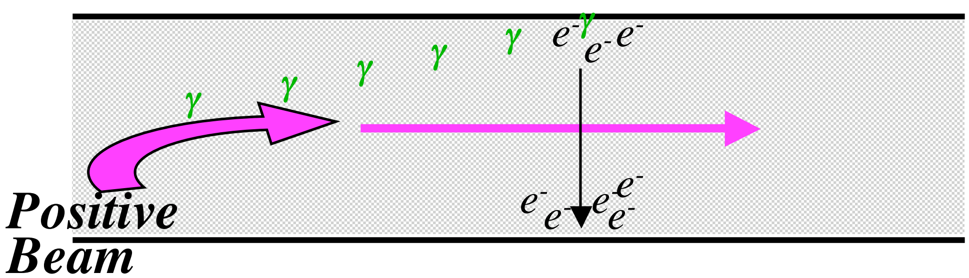
Ionization of background gas

$\Rightarrow$ expelled ions hit vacuum wall

Synchrotron radiation

"Secondary" electrons are made by electrons hitting the wall

Acceleration by the beam causes the electrons to multipy:



Beam-induced Multipacting

Importance of the Electron Cloud

Possible Consequences:

- **instability**
  - **e.g. head-tail instability**
  - **two-stream instability**
- **emittance growth (beam heating)**
- **excessive power deposition at cold walls**
- **interference with diagnostic instrumentation**
- **vacuum pressure rise**
- **particle loss**

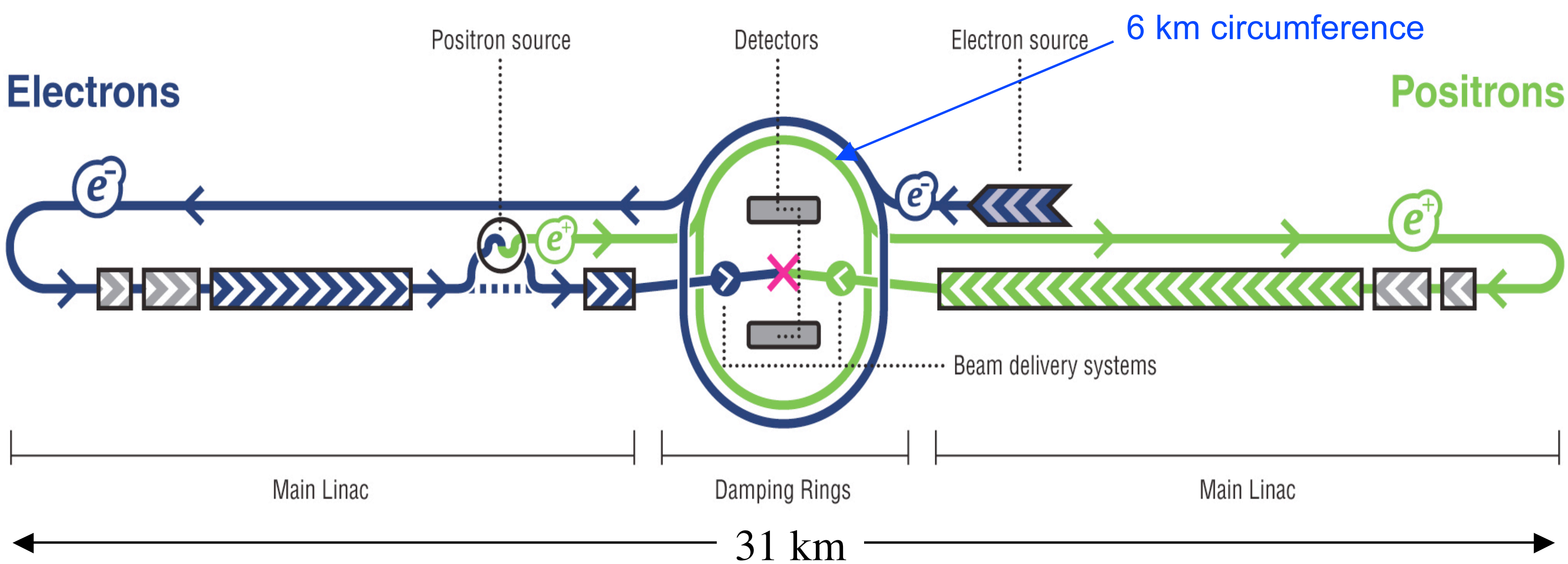
Effects have been observed at:

PF, PEP-II, KEKB, BEPC, PS, SPS (LHC beams), APS, PSR, RHIC, CESR, SNS (if provoked)

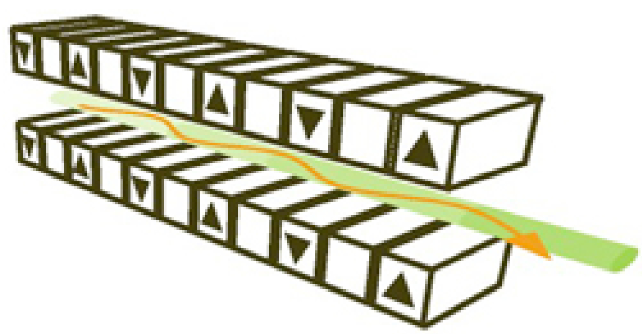
Expected at

LHC, ILC Damping Rings

Electron Cloud Effects are Important to the International Linear Collider Design



Positrons are “cooled” in the damping ring by sending them through a wiggler, causing them to emit synchrotron radiation.



Electron Cloud Effects are Predicted to Be Severe in the Positron Damping Ring

Beam current is very high ⇒ lots of synchrotron emission

Simulations predict:

Without any mitigations, cloud density high enough to cause beam instability and other effects.

Mitigations:

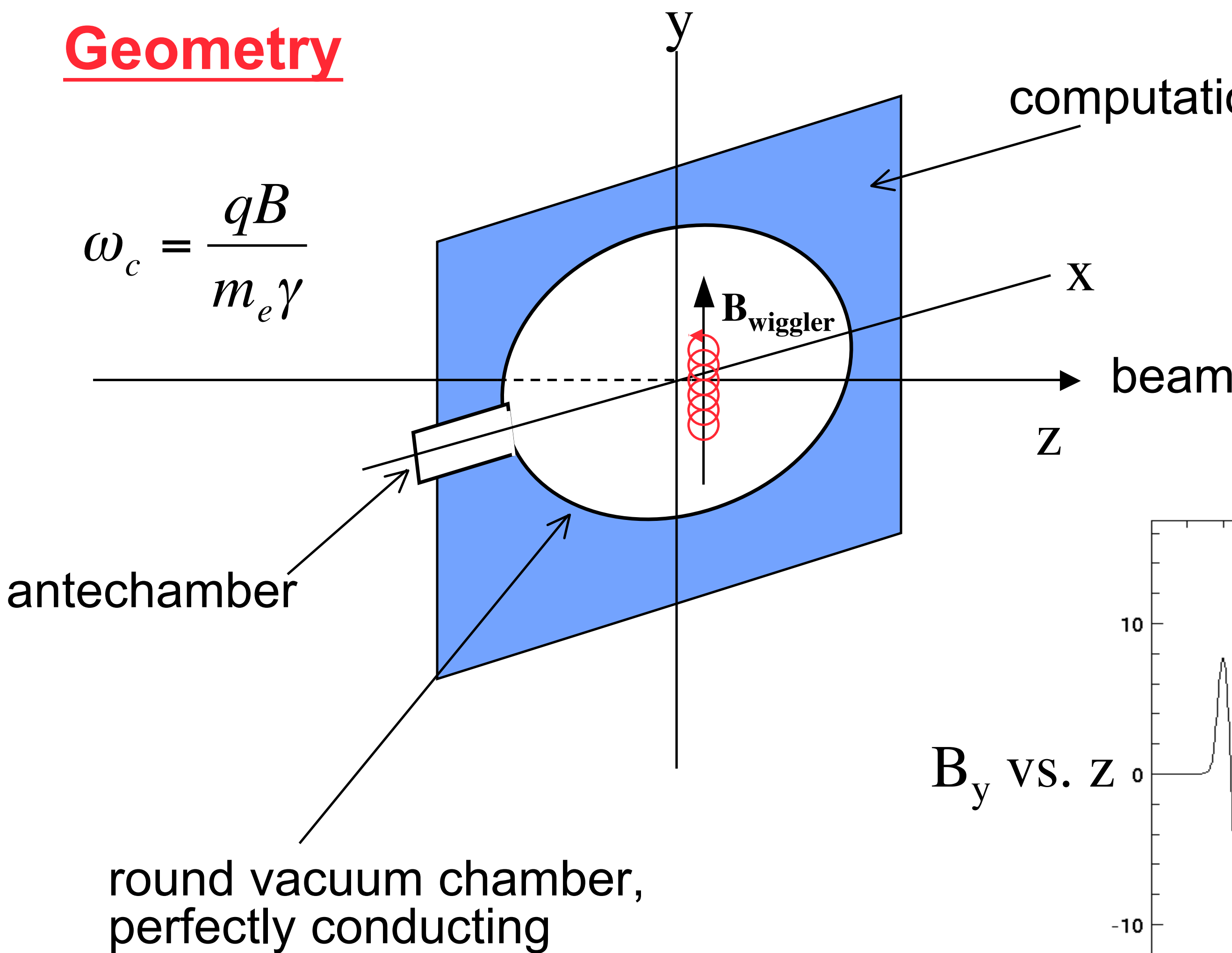
Wall treatments are planned, to reduce the secondary electron emission.

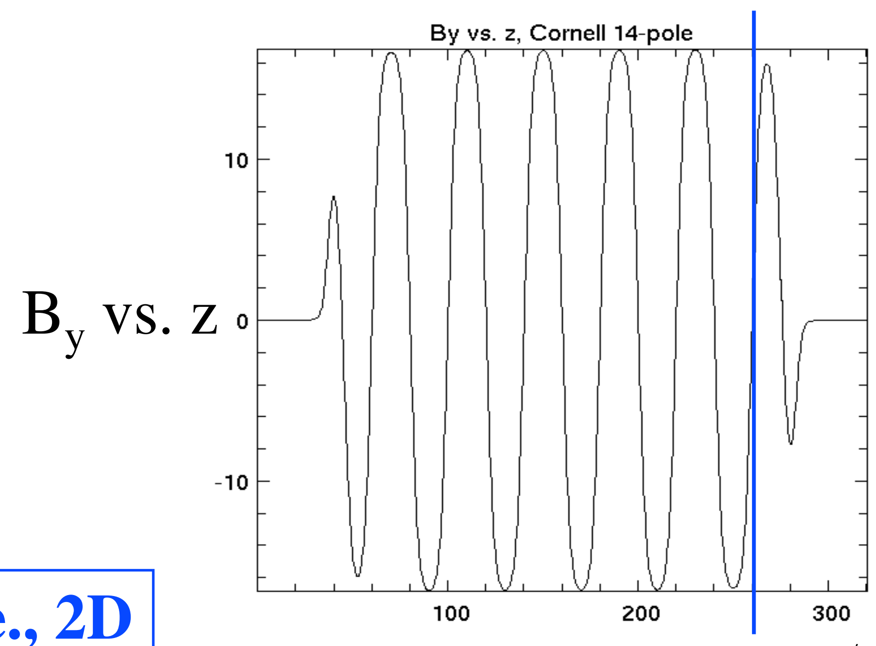
If the mitigations fail, two positron damping rings must be made instead of one, to lower the beam current--
a very expensive proposition!

We used POSINST, a 2D Computer Code, to Simulate x-y Slices of the Wiggler

Geometry

$$\omega_c = \frac{qB}{m_e \gamma}$$





E of beam is transverse - i.e., 2D

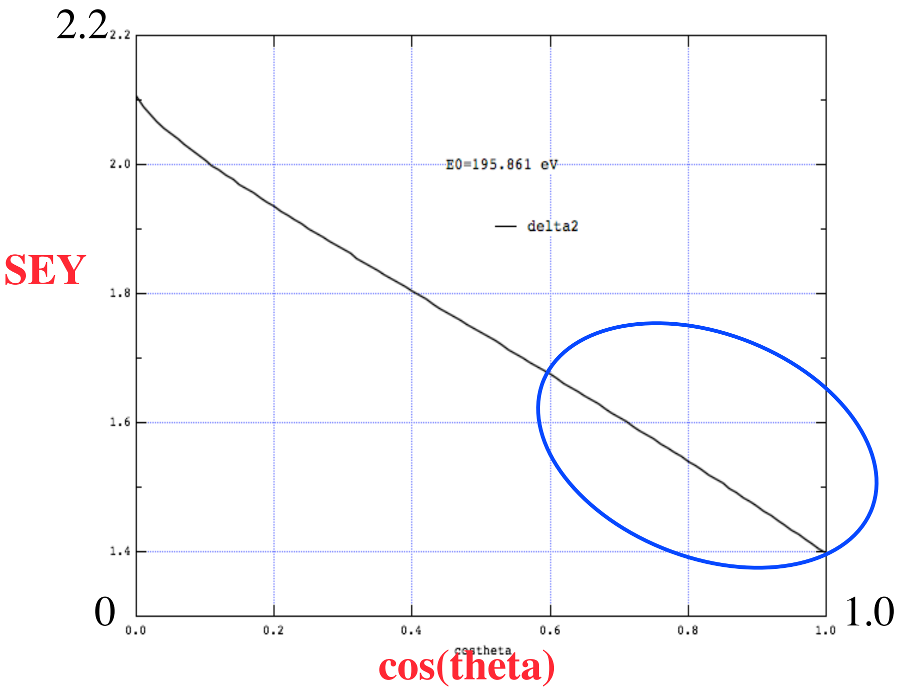
POSINST uses certain assumptions...

- Beam does not evolve in time (OK for short times, e.g., buildup)
- Beam electric field is transverse only (relativity)
- Beam magnetic field neglected (v_e small)
- Electrons generated according to phenomenological models

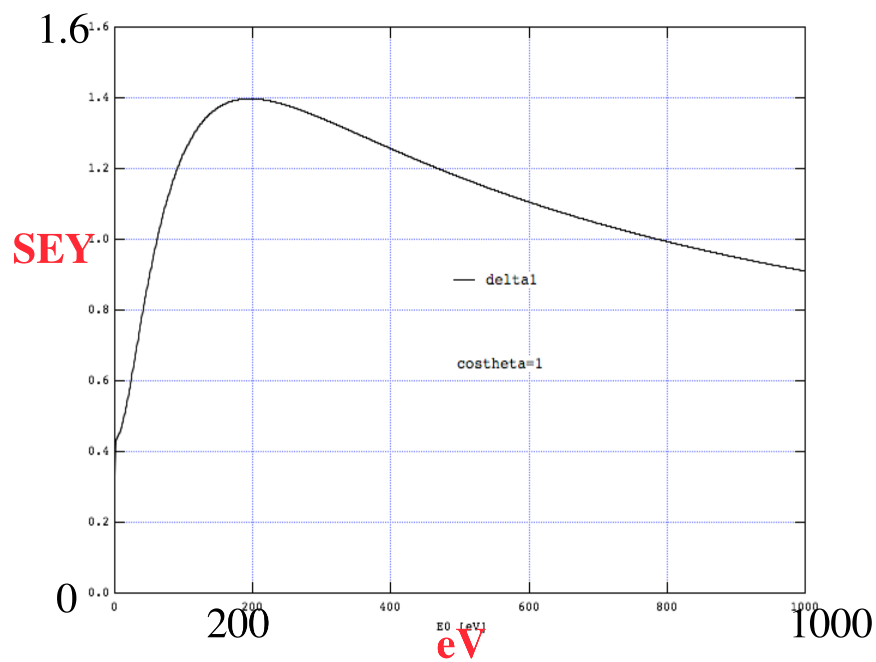
  secondaries: Furman-Pivi (next slide)

The force of the electrons on each other as it evolves in time is calculated self-consistently by a Particle-in-Cell algorithm.

Electron energy & incident angle determine secondary electron yield (SEY)



SEY at Normal Incidence



Quantitatively- only about 15% drop from cos of 0.6 to 1.0.

SEY triples from 0 to 100 eV
20% more from 100 to 200 eV.

The "Particle-in-cell" (PIC) Algorithm Follows Representative Macroparticles

We start with a sample of the electrons at a given time

Calculate the self field using charge deposition to a grid of cells

Calculate the image forces, add the external forces to get the total force,

And move the particles.

this enables a

Self-Consistent Space Charge Calculation for the electrons

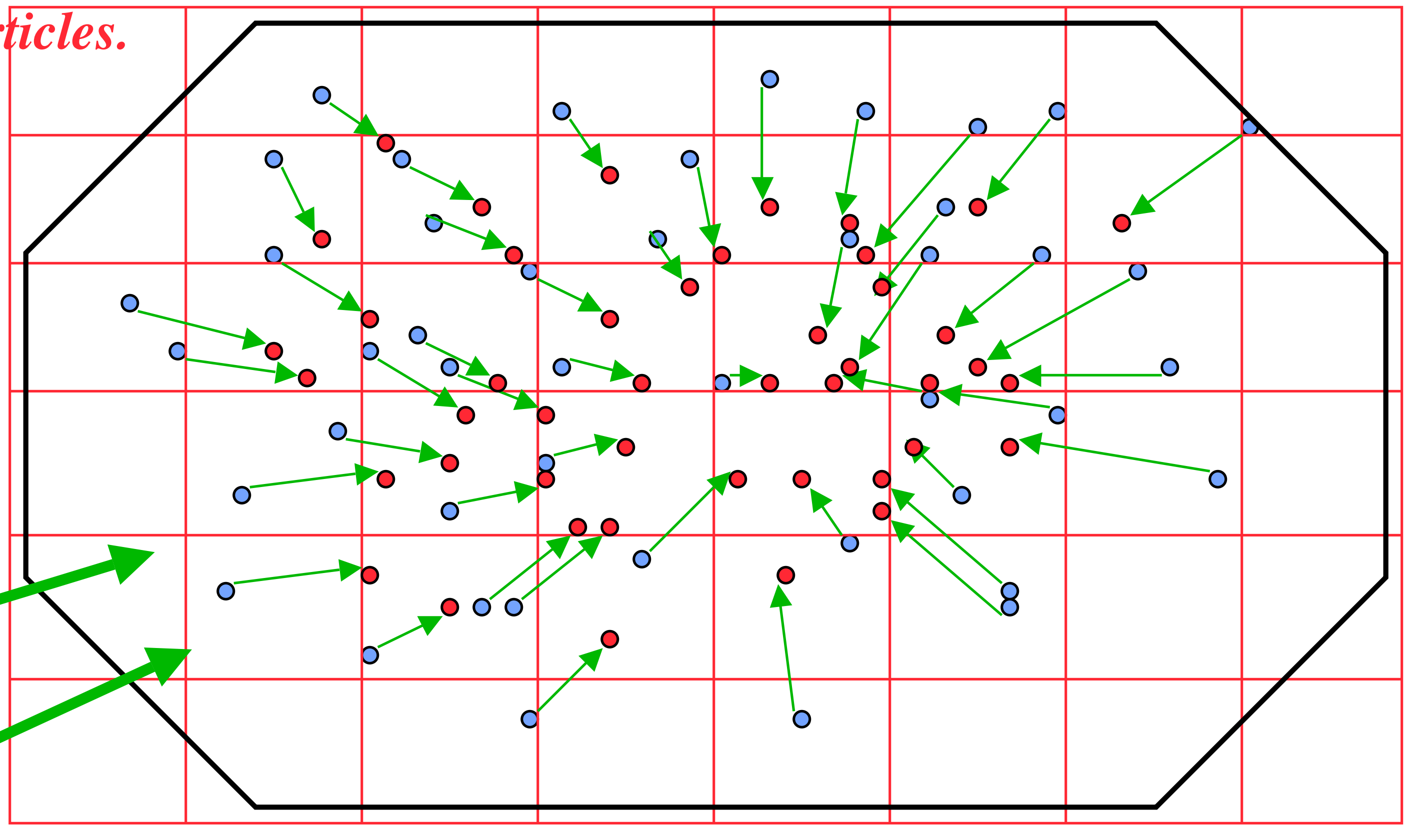


Image Forces

External Forces

Cloud Buildup Calculations were done using ILC Damping Ring Parameters

"Wiggler":

$B_y \leq 1.6$ T; $B_x = B_z = 0$ (ideal dipole)

Vacuum Chamber:

R = 2.3 cm (vacuum chamber radius)

Antechamber full height = 1 cm

Beam:

2×10^{10} e+ per bunch

9 GeV

$\sigma_x = 0.112$ mm, $\sigma_y = 4.6$ μm, $\sigma_z = 6$ mm

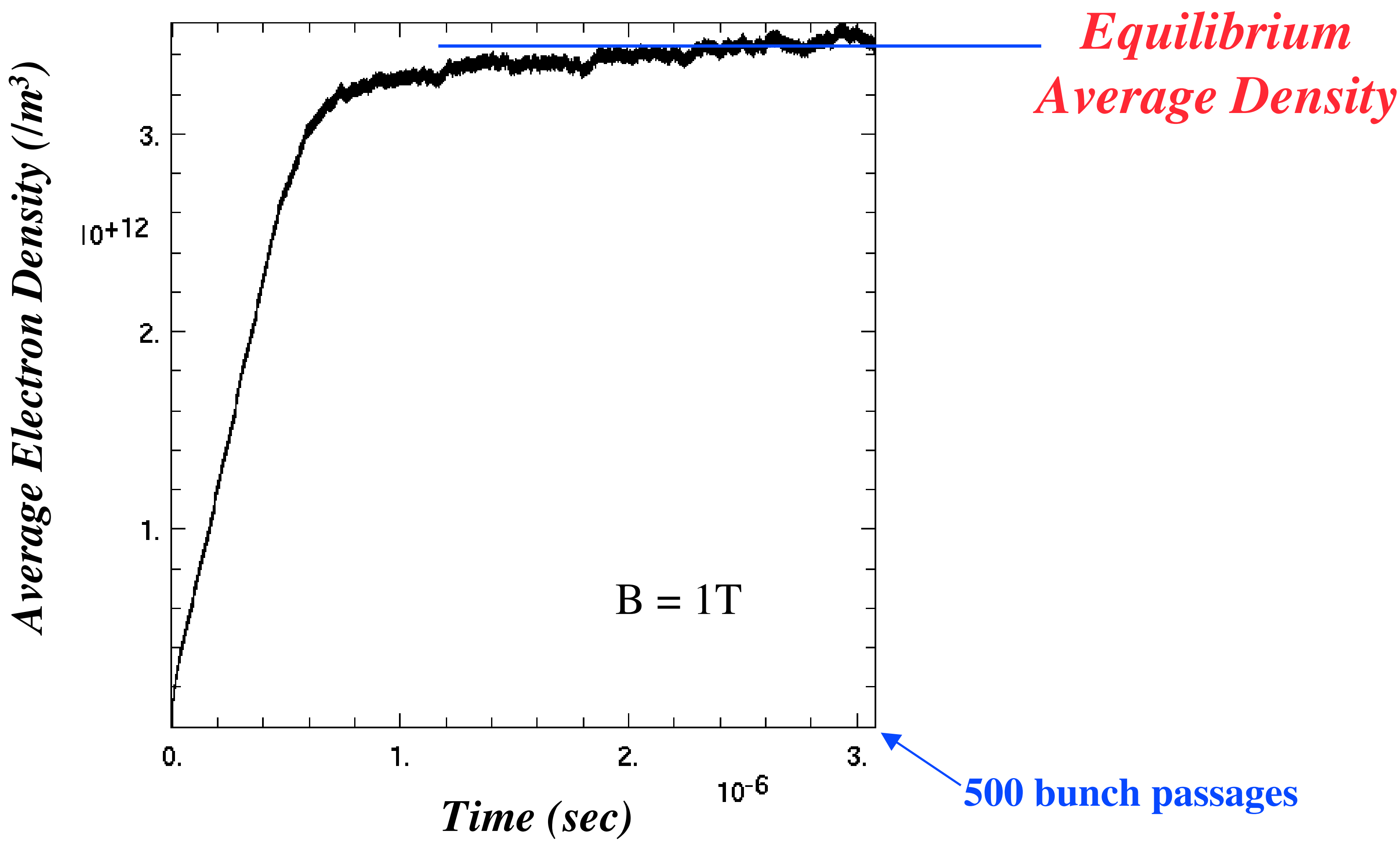
bunch spacing: 6.15 ns

Electron Production:

photon reflectivity = 1

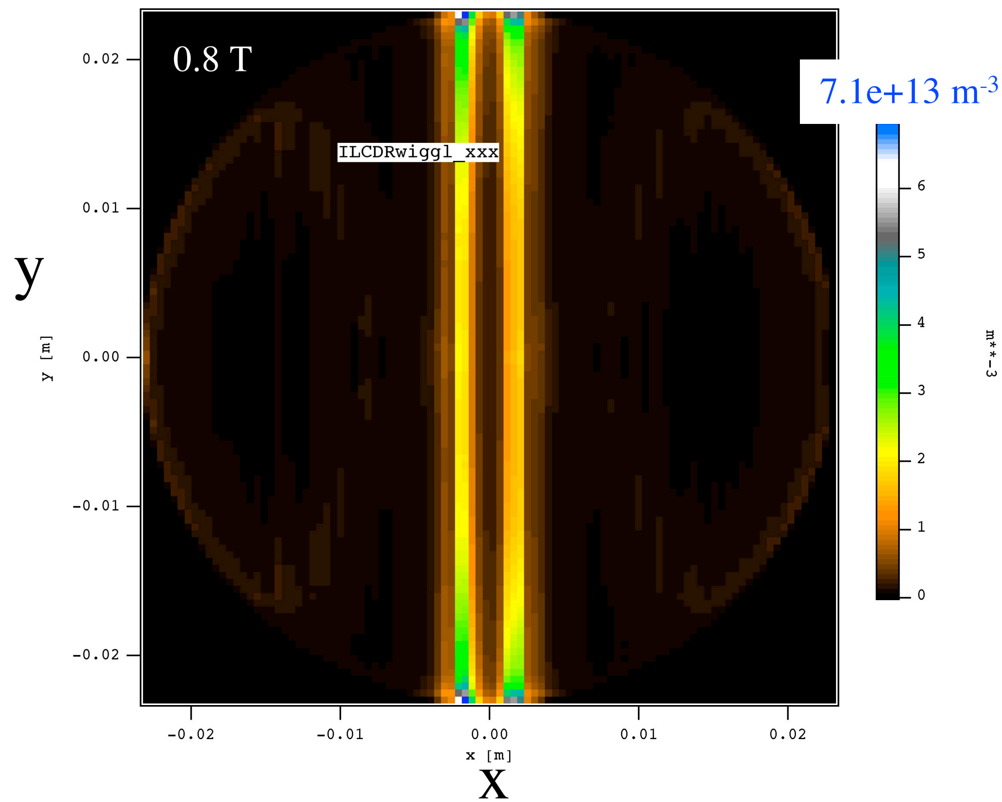
peak SEY @ normal incidence = 1.4

For a Given B, the Average Electron Density Builds Up over Time, then Plateaus



Multipactoring causes "stripes" of high density in the electron cloud

Density Distribution Averaged over Run (POSINST)
X-Y Plane

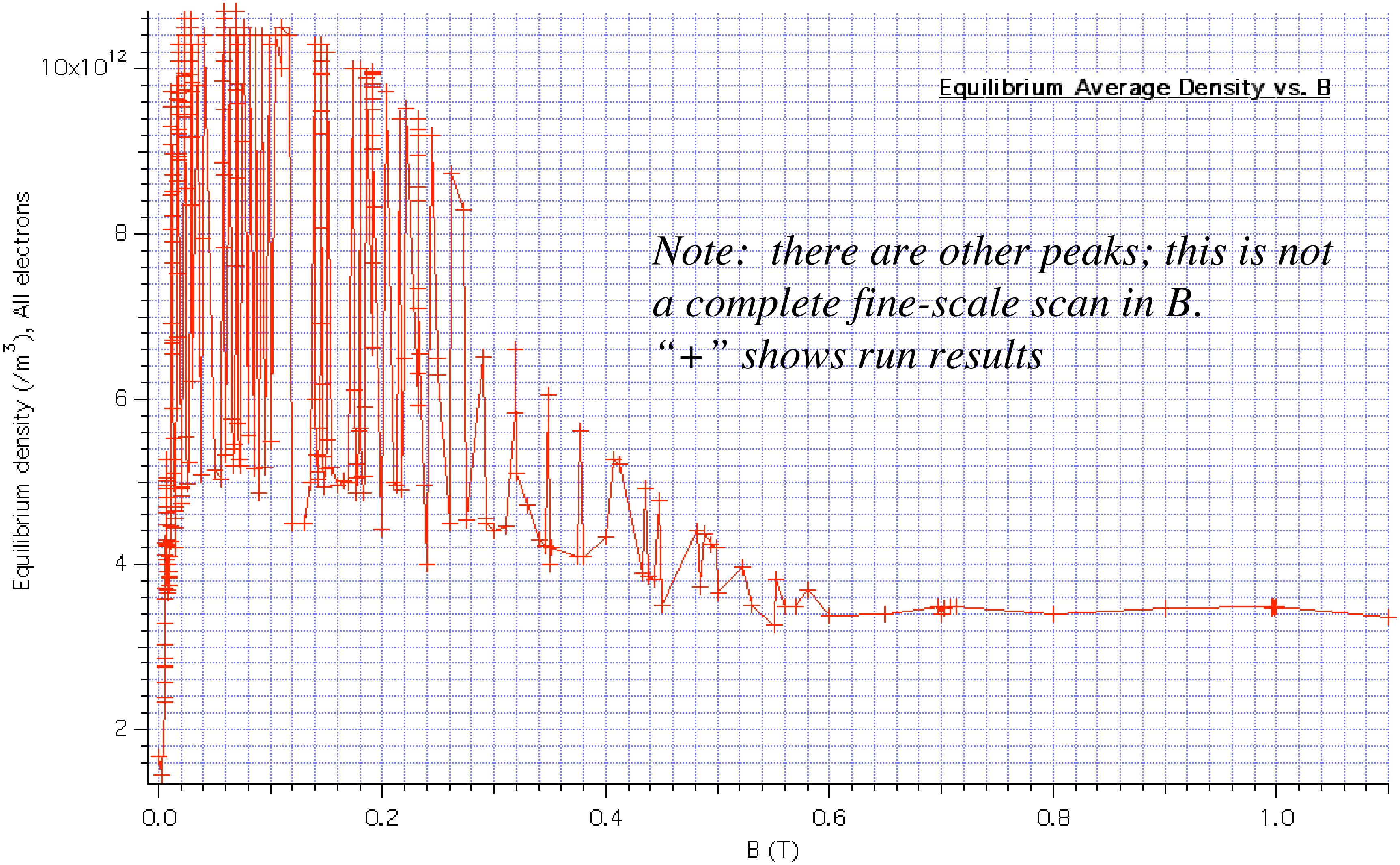


B = 0.8 T

Next Question:

What happens as z, and therefore B, changes in the wiggler?

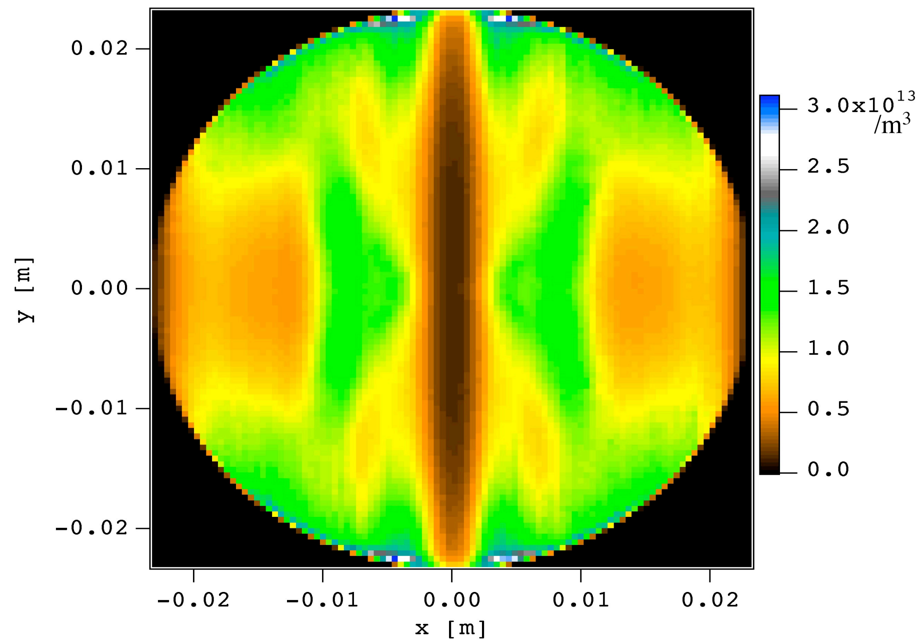
Average Equilibrium Density vs. B has Peaks at Low B!



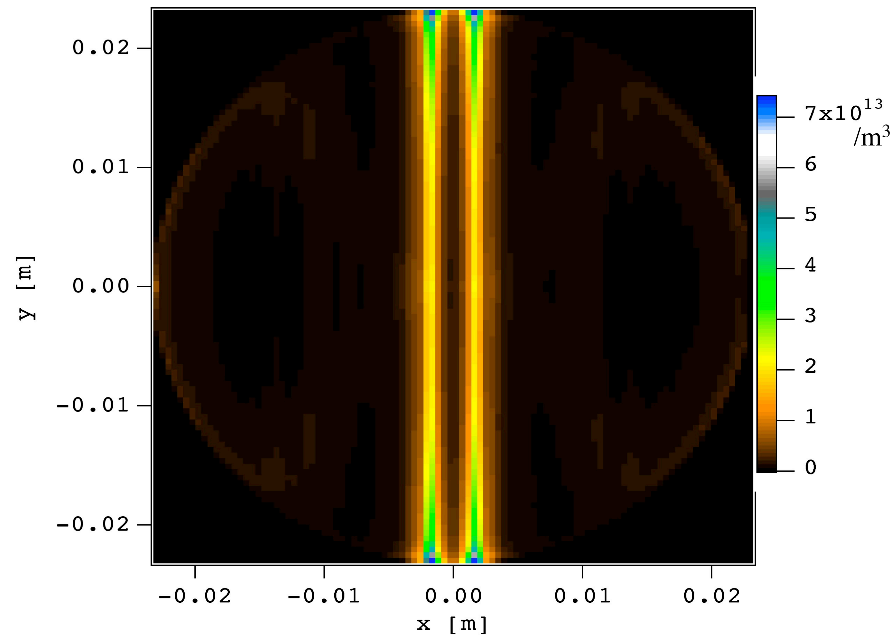
Density at peaks is up to 3x its value at high B.

Another effect, from POSINST Simulation: Electrons more Dispersed in Resonant Case

Density Distribution Averaged over Run (POSINST)
X-Y Plane



B at a spike



High B

A Hypothesis

If:

The **bunch spacing** is an integral multiple of the **cyclotron period**

Then:

Each time the electron gets a push from the beam field, it is in the same position ⇒

Resonance

Important:

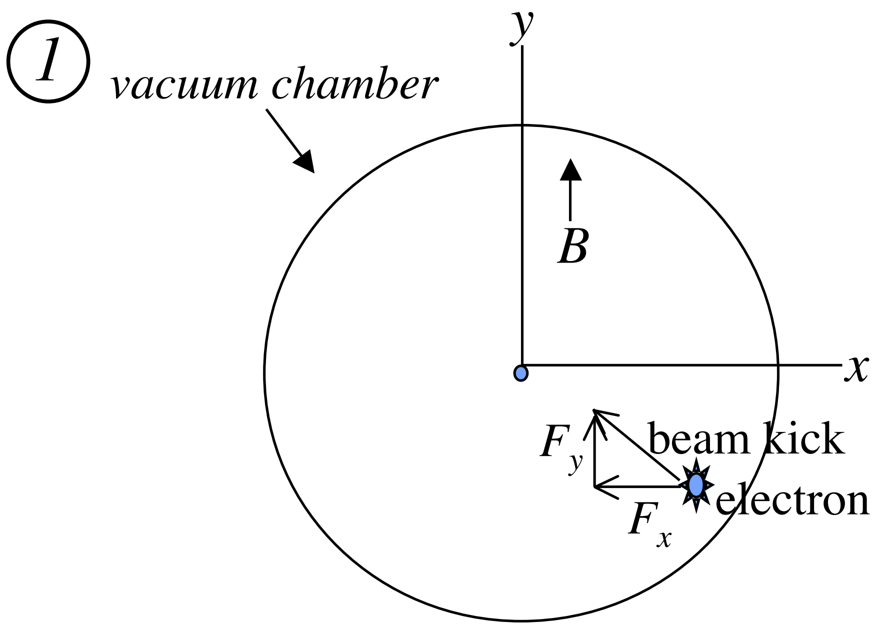
Cyclotron period is function only of B for v<<c.

$$\tau_c = \frac{2\pi m_0 \gamma}{qB}$$

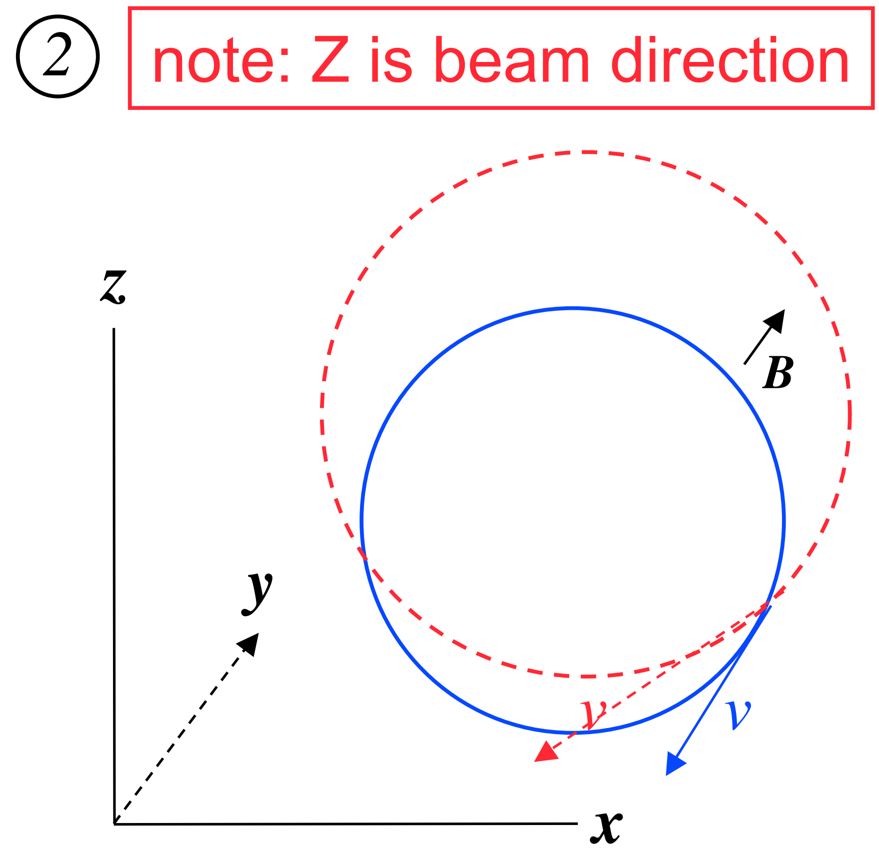
γ = relativistic factor

So electron stays in resonance until detuned by relativistic mass increase or space charge.

How it Works

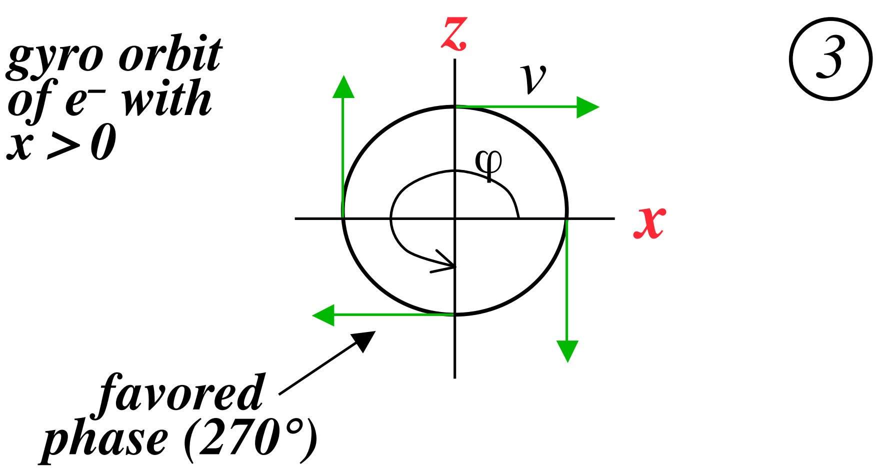


F_x is always toward the center



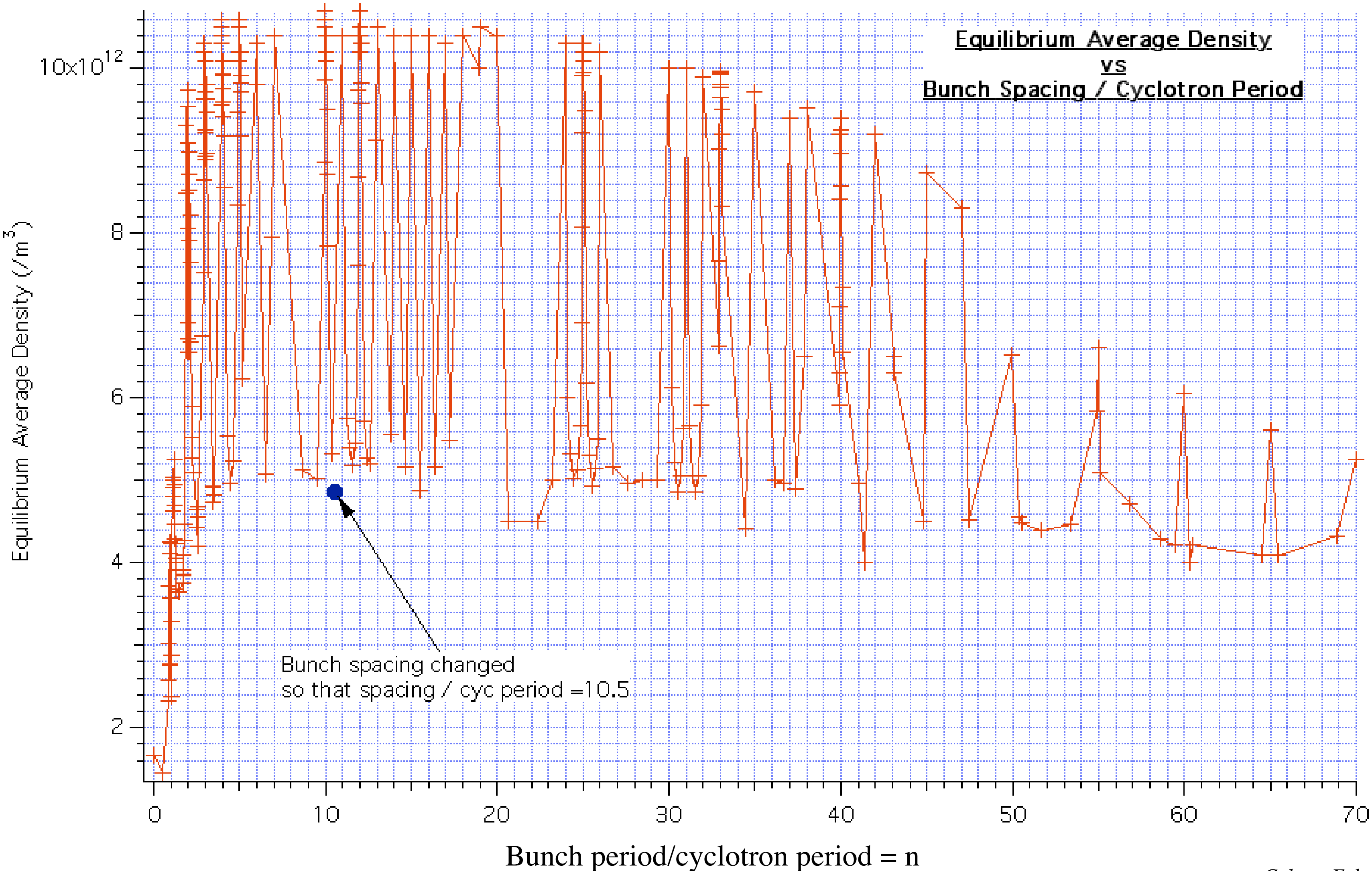
– *before beam kick*

– *after beam kick*



Peaks all fall on Integral Values

Note: some peaks (and dips) missing because runs have not yet been done at that field



Investigation of Dynamics Using a Single-Particle Tracking Code

A Small Tracking Code was Written to Look at Individual Particle Dynamics

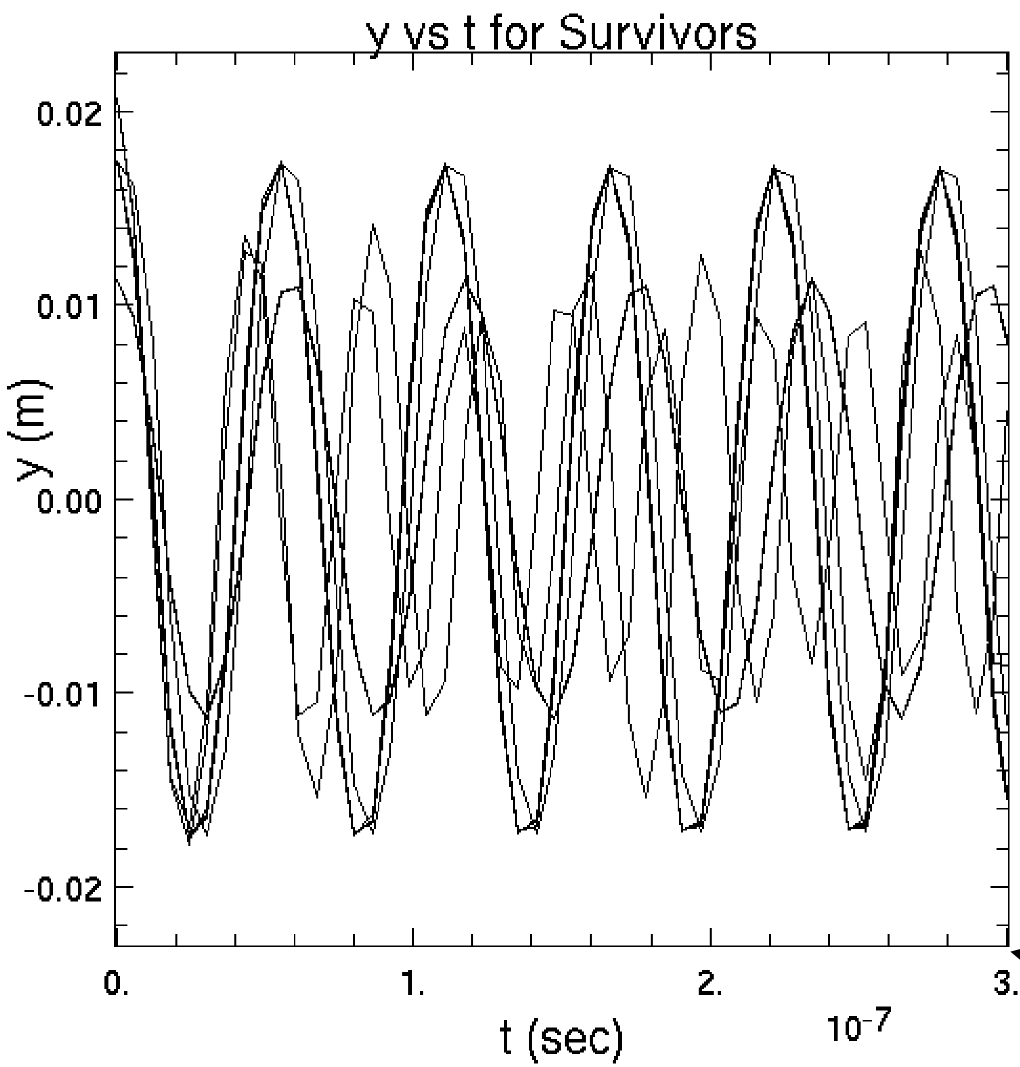
- Particles begin at top wall of vacuum chamber with $x \geq 0$
- Space charge neglected (OK at early times)
- Beam force modeled as instantaneous kick
- 3D dynamics tracked

let $n \equiv$ (beam bunch period) / (e^- cyclotron period, $\gamma=0$)

$$= \frac{qB\tau_B}{2\pi m_0}$$

τ_b = bunch period

A Small Fraction of Electrons Oscillate in y for Many Bunch Passings

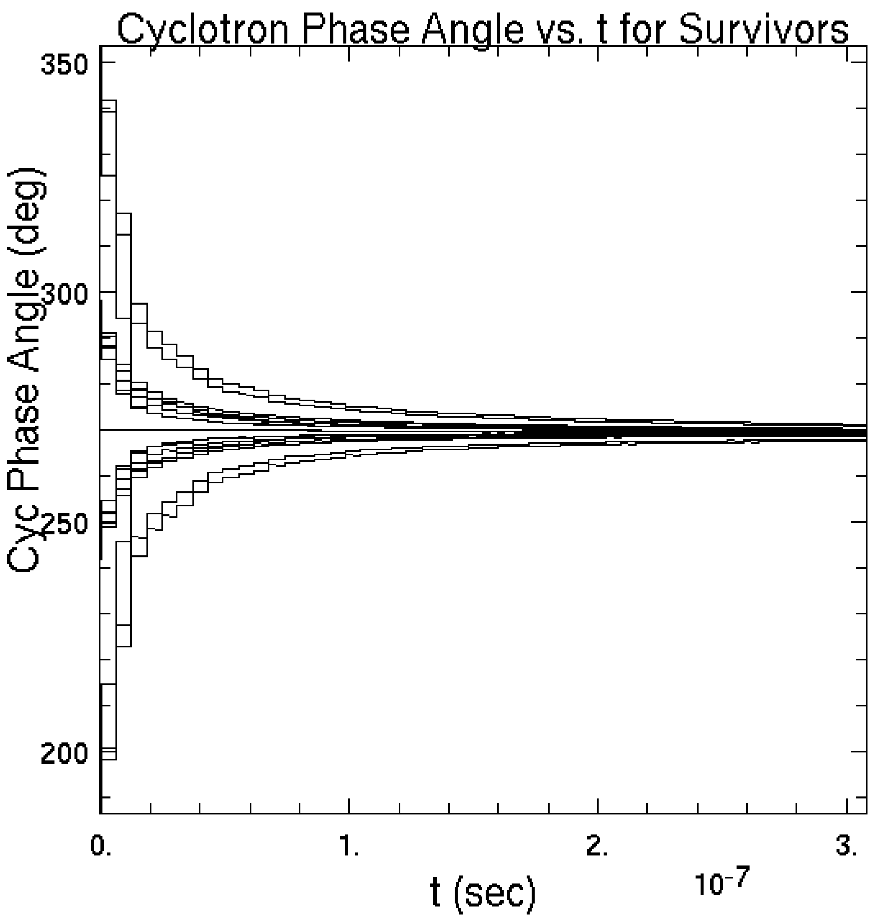


50 bunch passes

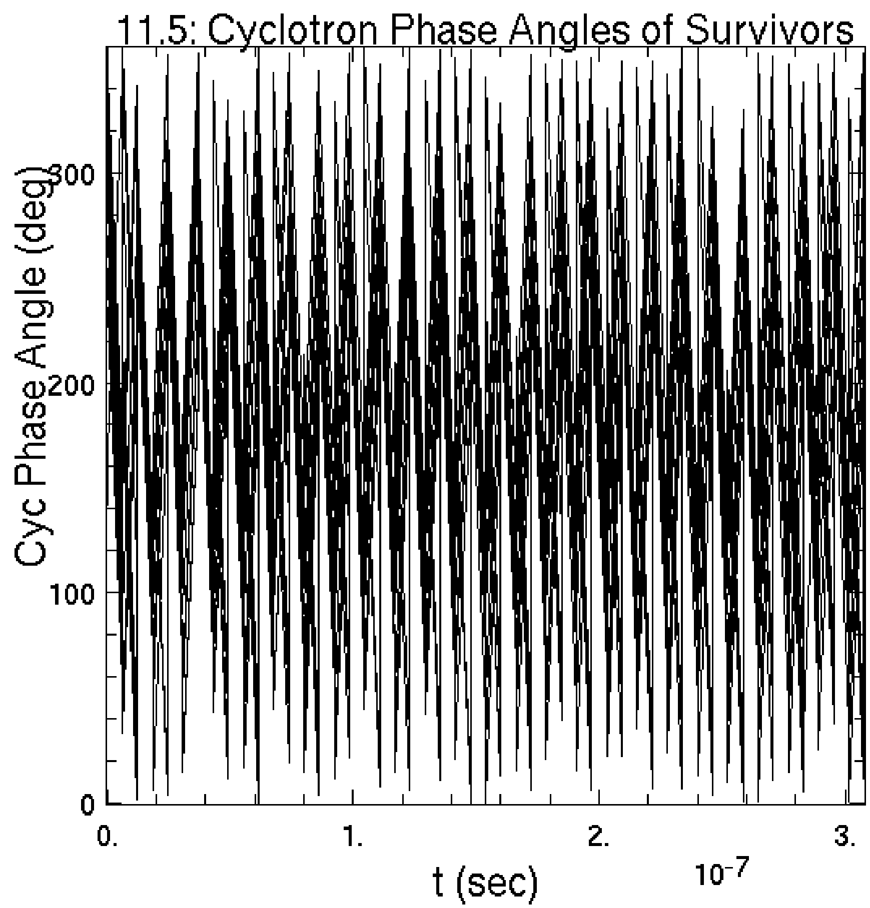
These "survivor" electrons stay in the system for > 50 bunch passages, so they are good for demonstrating long-term effects of the resonance.

Cyclotron Phase Angle vs. t for "Survivor" Electrons - non-relativistic calculation

n=12 (resonant case)



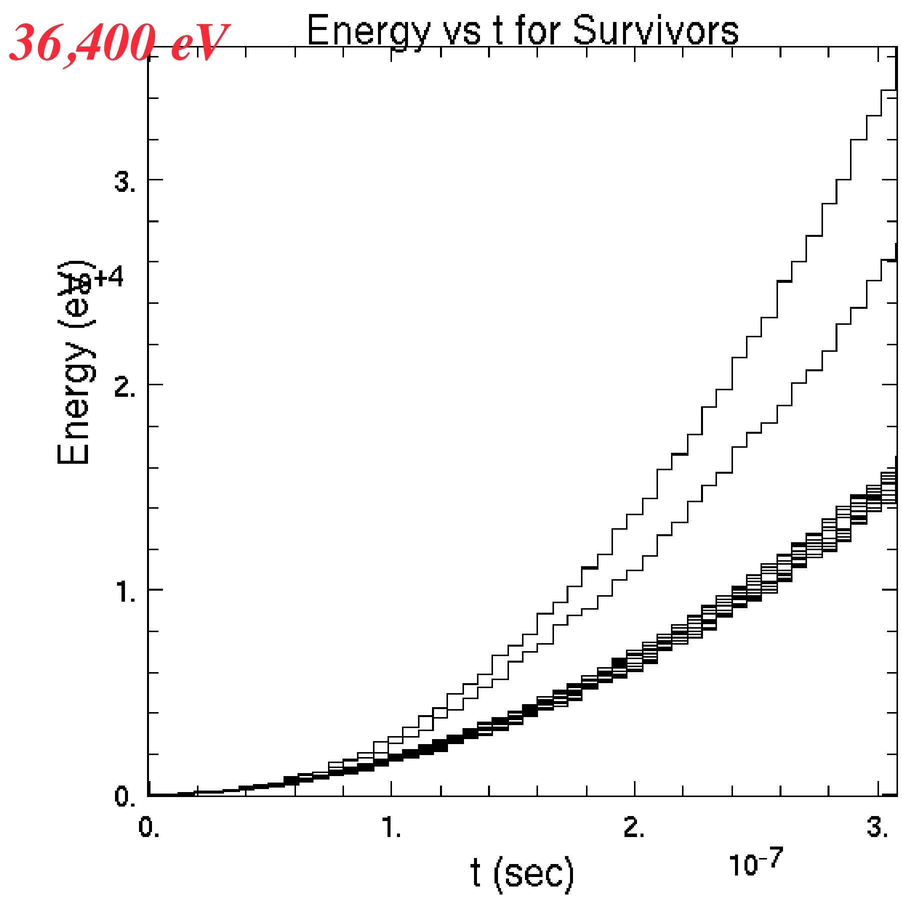
n=11.5 (nonresonant)



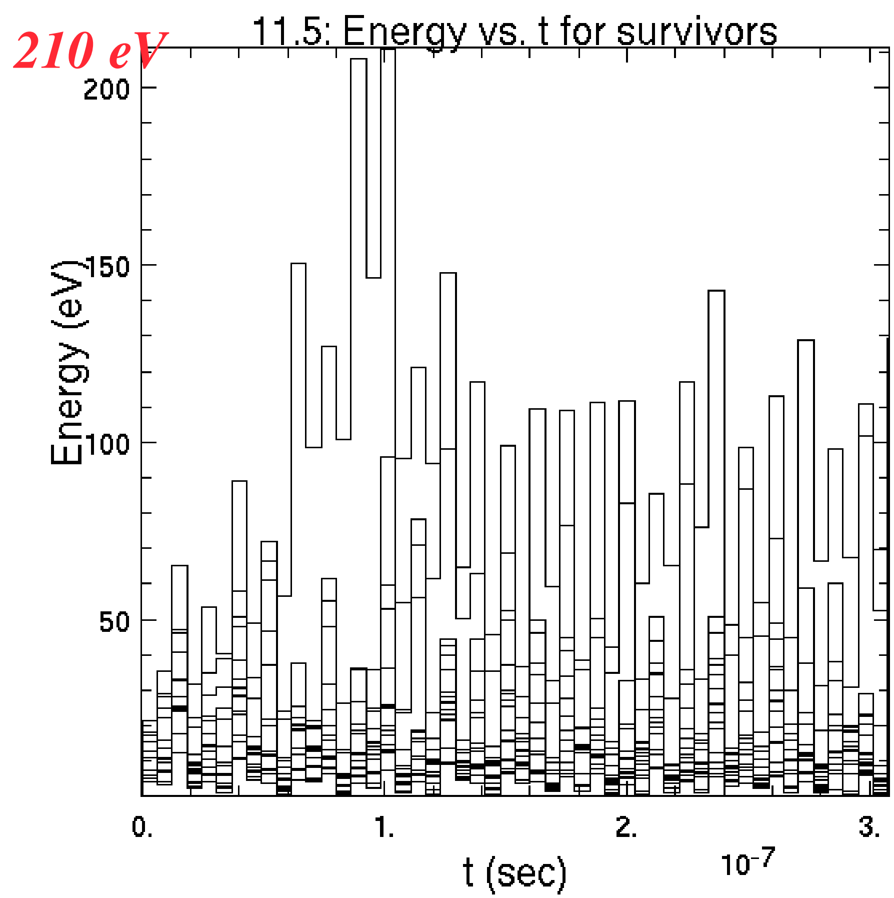
Cyclotron phase angle goes to 270°, as predicted, for resonant case, but not for nonresonant.

Energy Growth much larger for Resonant than Non-resonant Case (nonrel. calc.)

n=12 (resonant case)



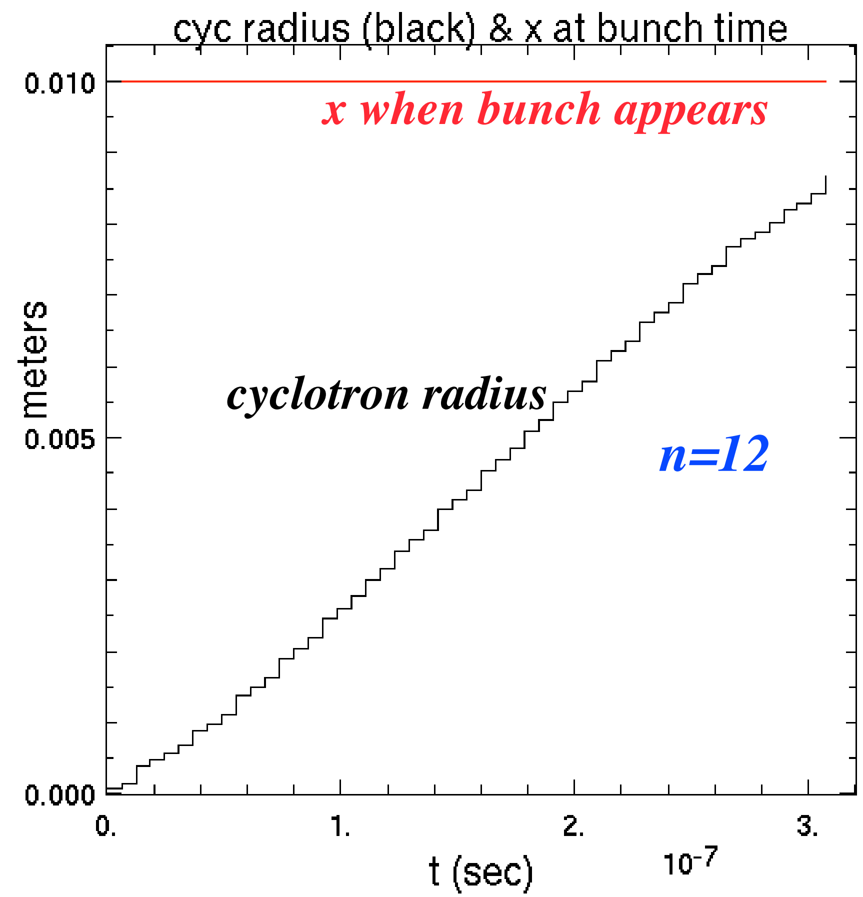
n=11.5 (nonresonant)



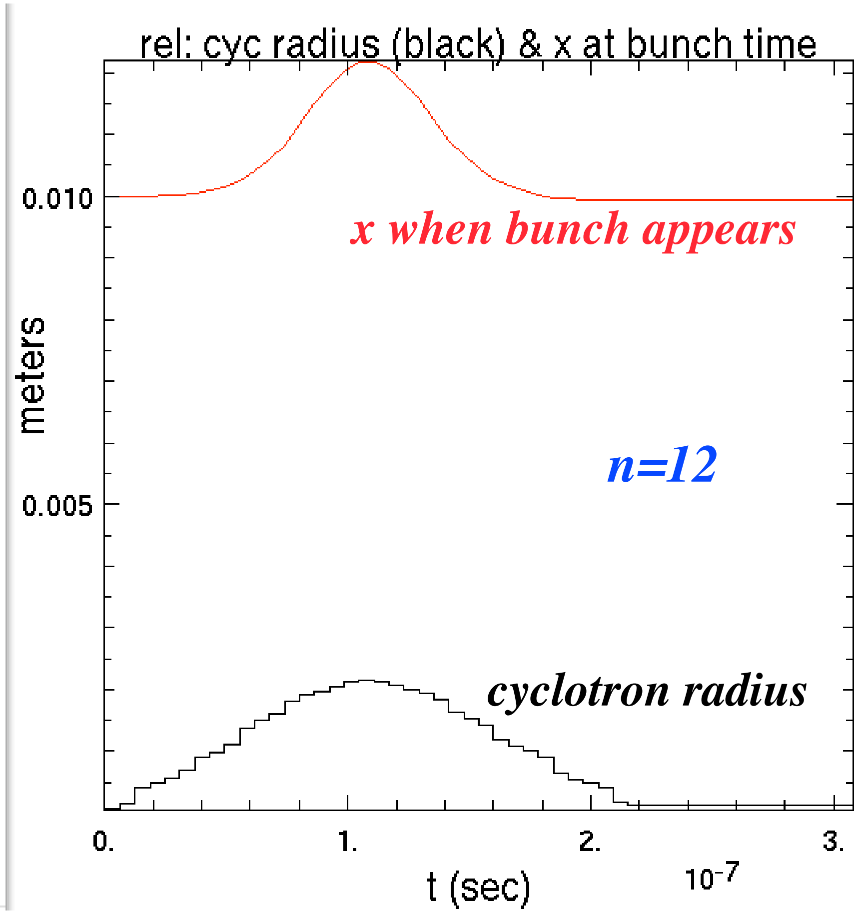
Energy grows to very large values for resonant case, but not for nonresonant.

With Proper Relativistic Dynamics, Mass Increase Detunes Electron from Resonance

Non-relativistic dynamics



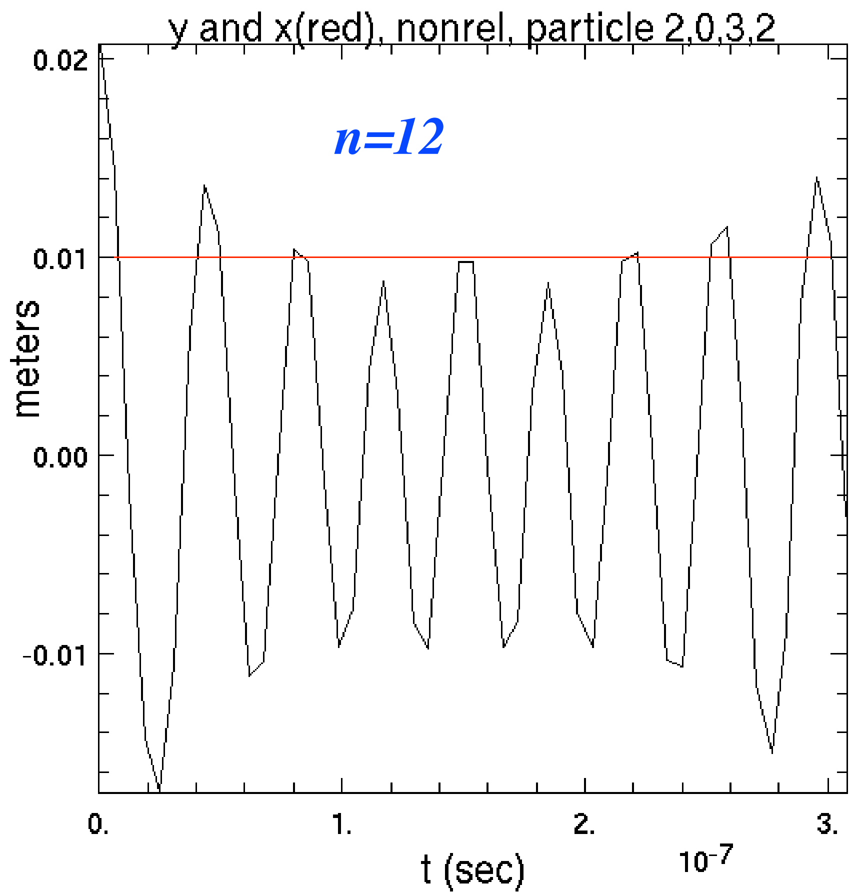
Relativistic dynamics



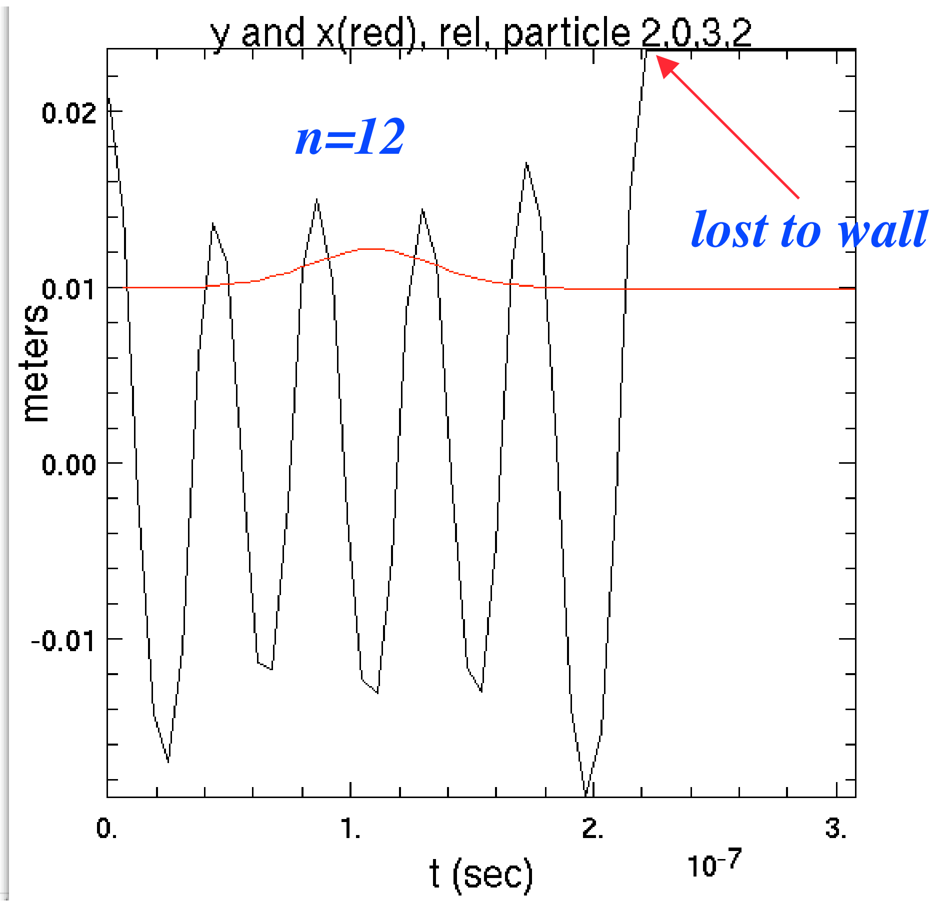
In non-relativistic case, x always same when bunch returns. In relativistic case, goes out of phase as mass increases, and then momentum (and ρ) drops

y-oscillating Electrons don't Survive as Long in Relativistic Calculation

Non-relativistic dynamics



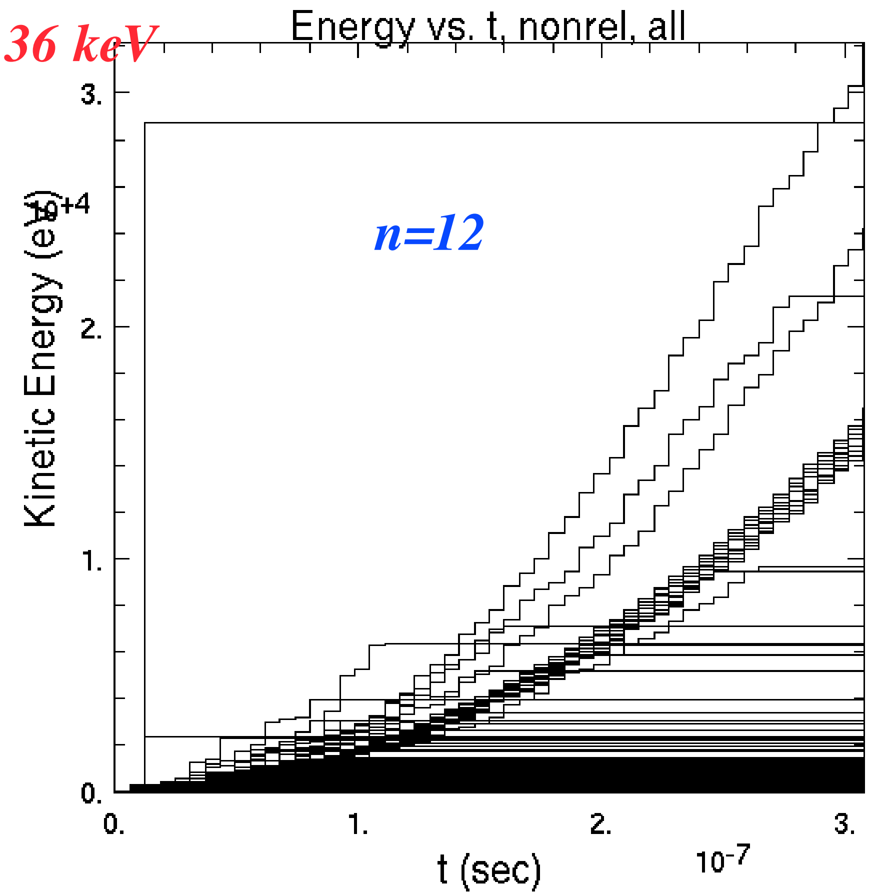
Relativistic dynamics



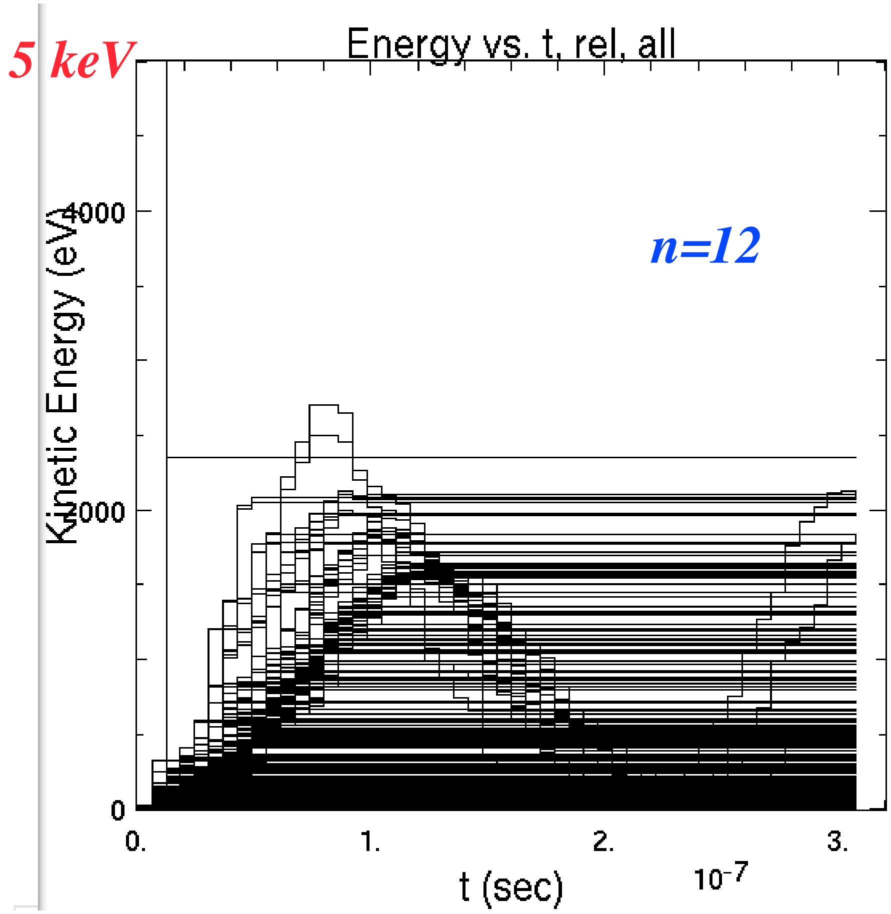
In relativistic case, oscillating particles hit the wall sooner. So final energy is lower than the non-rel. case, but they still have relatively high energies, and hit the wall and produce secondaries more often.

Final Energies- Smaller than Non-relativistic Case and Match the Simulation Better

Non-relativistic dynamics



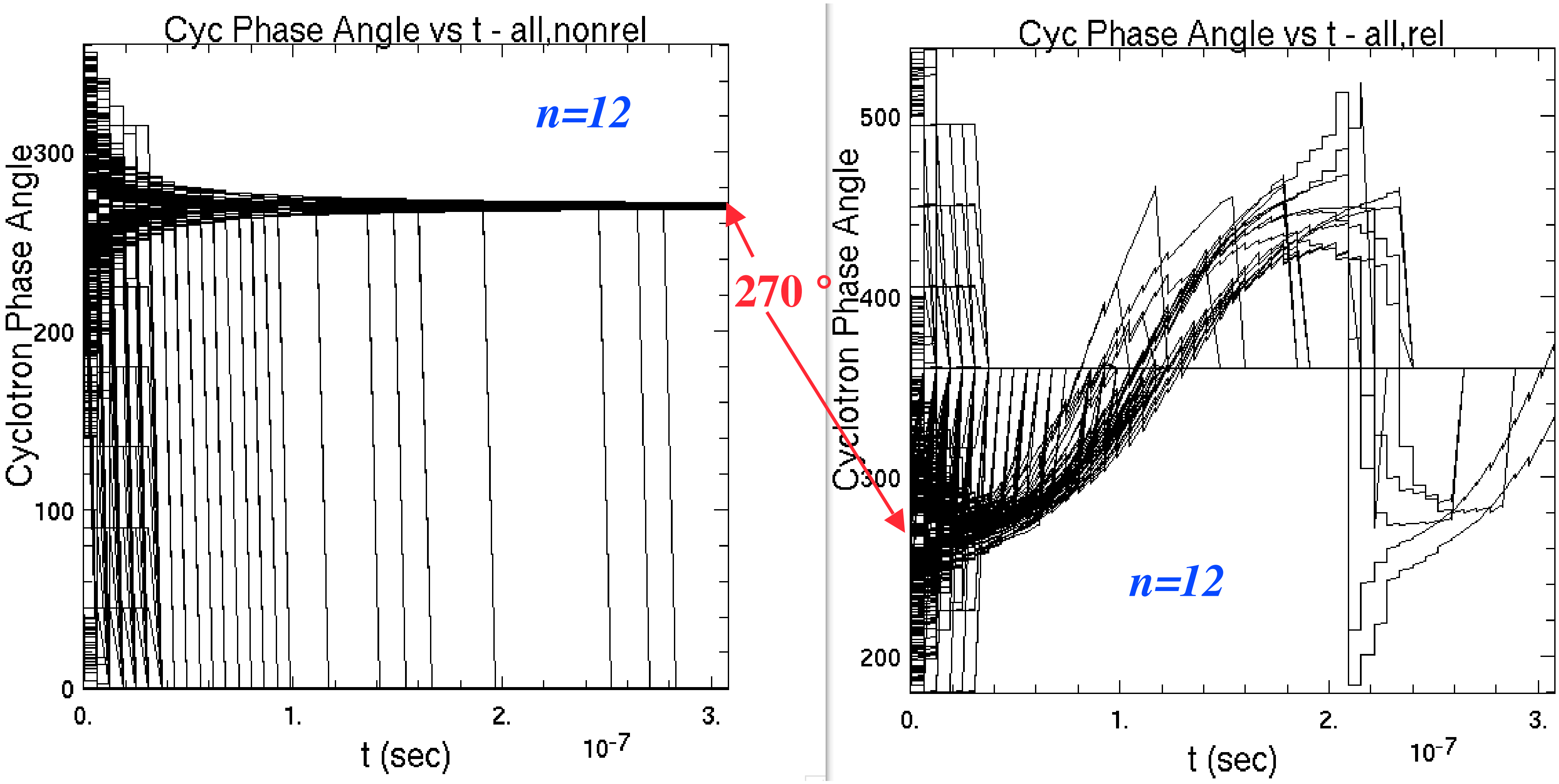
Relativistic dynamics



Note: when electrons hit the wall, their energy stops changing (horizontal line)

Cyclotron Phase Angle vs. t Also Shows Electrons Going In and Out of Phase

Non-relativistic dynamics *Relativistic dynamics*



Note: when electrons hit the wall, their angle is set to zero (gives vertical lines)

***Conclusion*: This small tracking code clearly shows the expected effect, and indicates the mechanisms for average SEY increase. It cannot, of course, find the equilibrium average density level.**

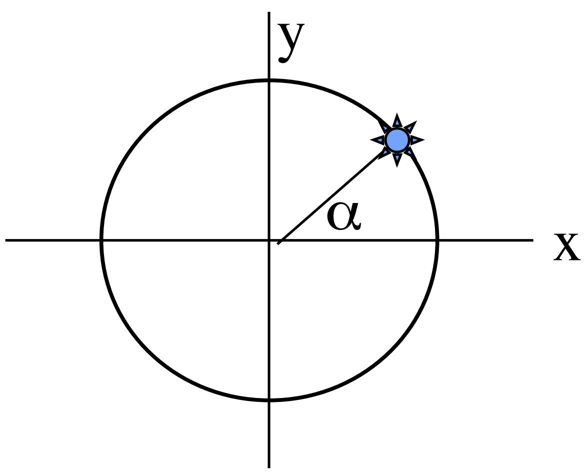
Does the Simulation Agree?

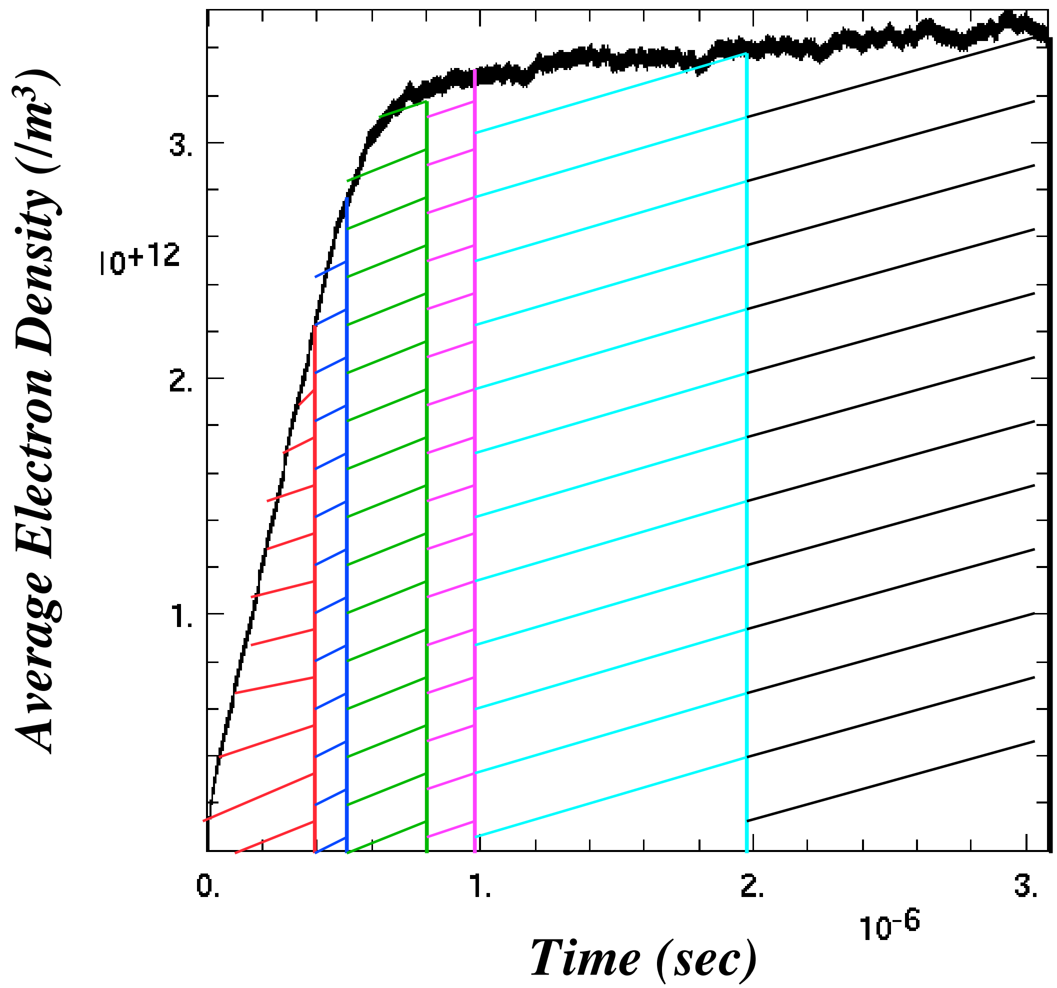
Note: Tracking results apply only while space charge is negligible.

Data will be shown by time interval

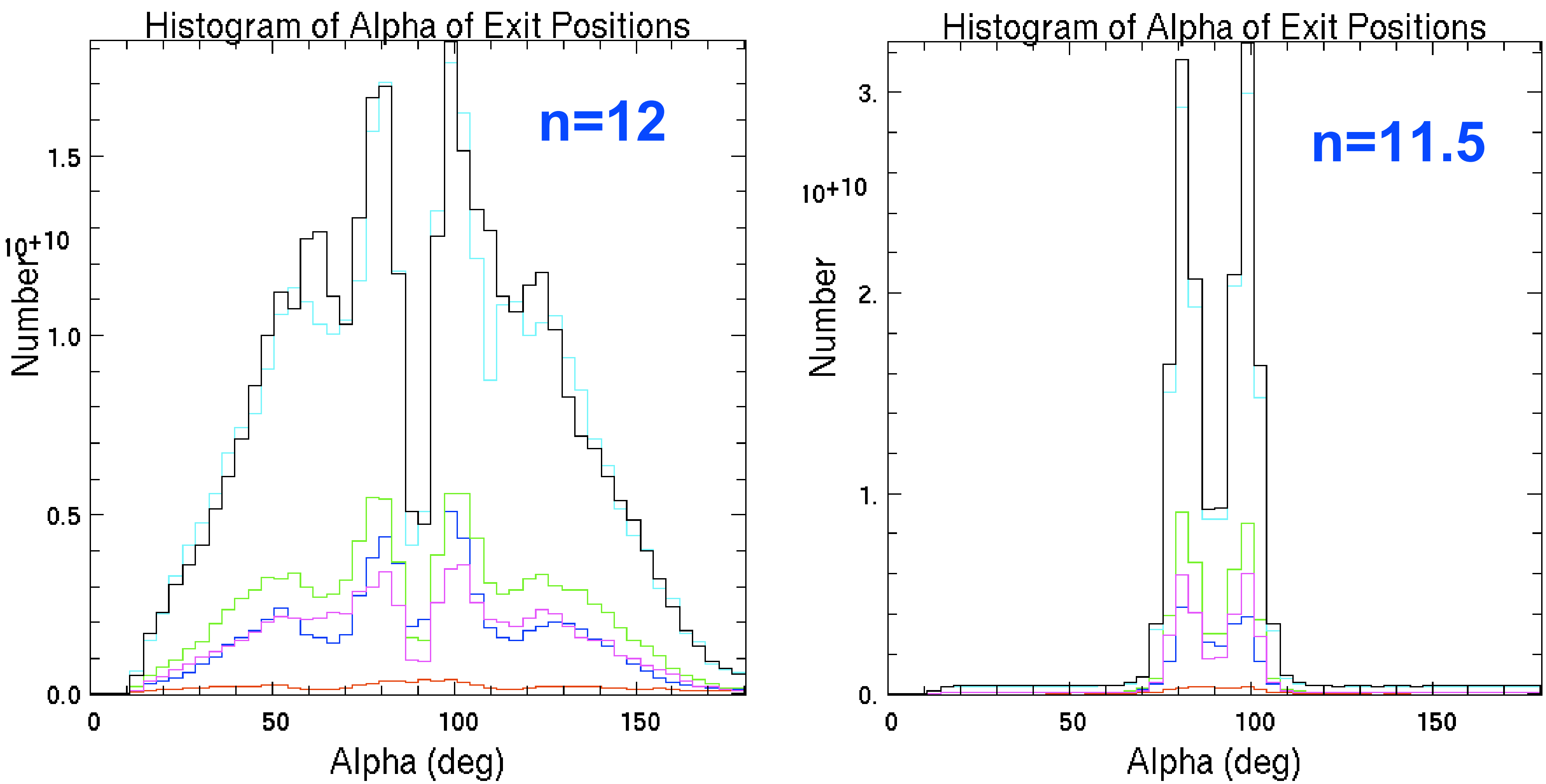
Color code:

0.0 - 0.2 ms
0.2 - 0.5 ms
0.5 - 0.8 ms
0.8 - 1.0 ms
1.0 - 2.0 ms
2.0 - 3.2 ms





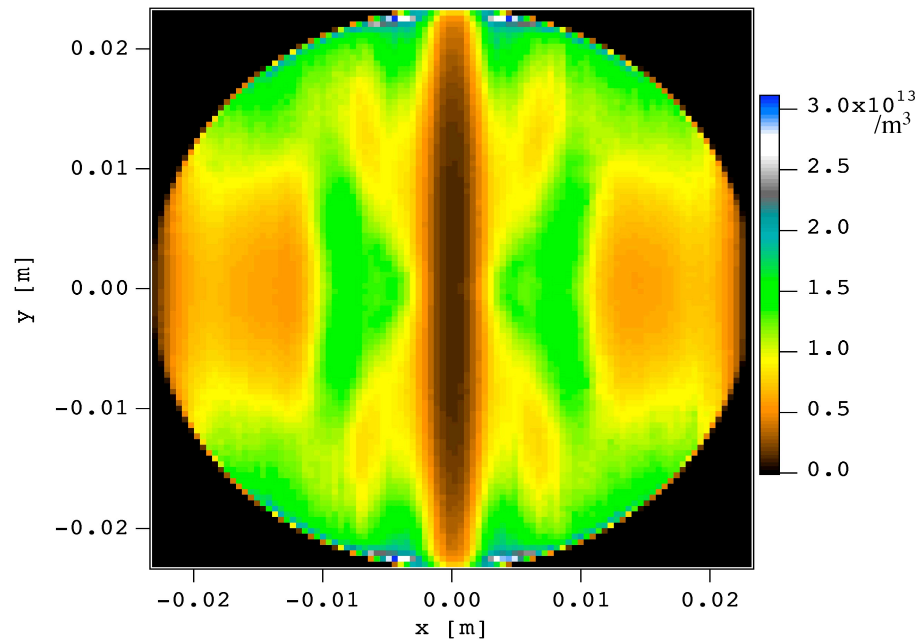
POSINST Data on electrons hitting the wall show very different pattern at resonance



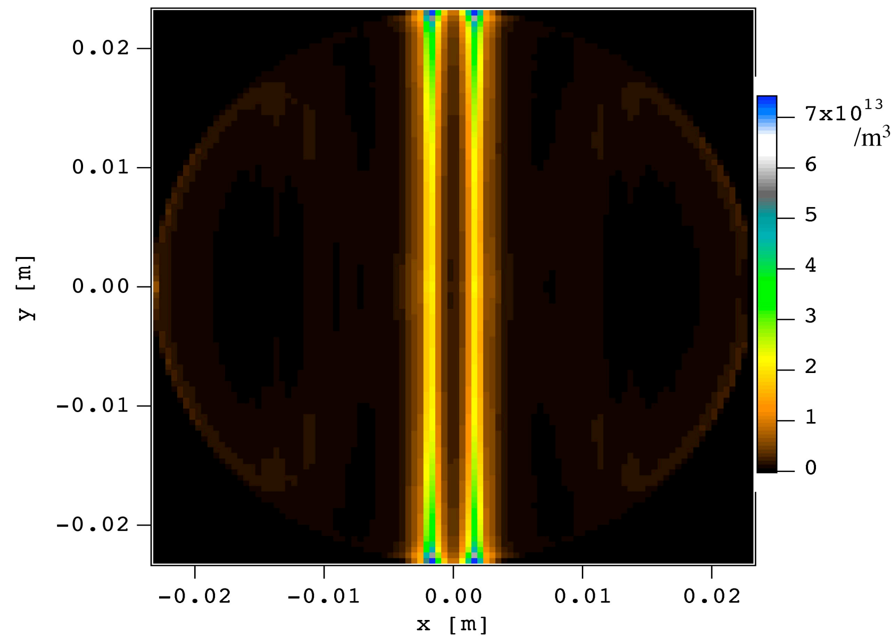
This is consistent with the “stripes” density distribution data that we saw before. Alpha = polar angle measured from x axis of vacuum chamber.

Another effect, from POSINST Simulation: Electrons more Dispersed in Resonant Case

Density Distribution Averaged over Run (POSINST) X-Y Plane

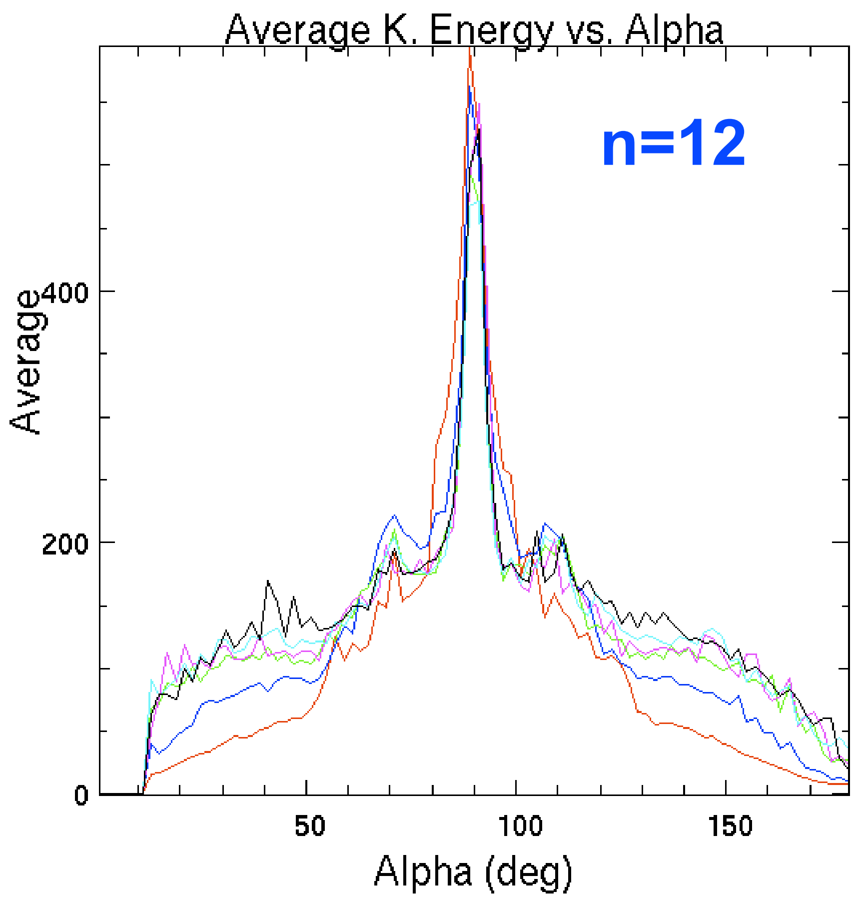


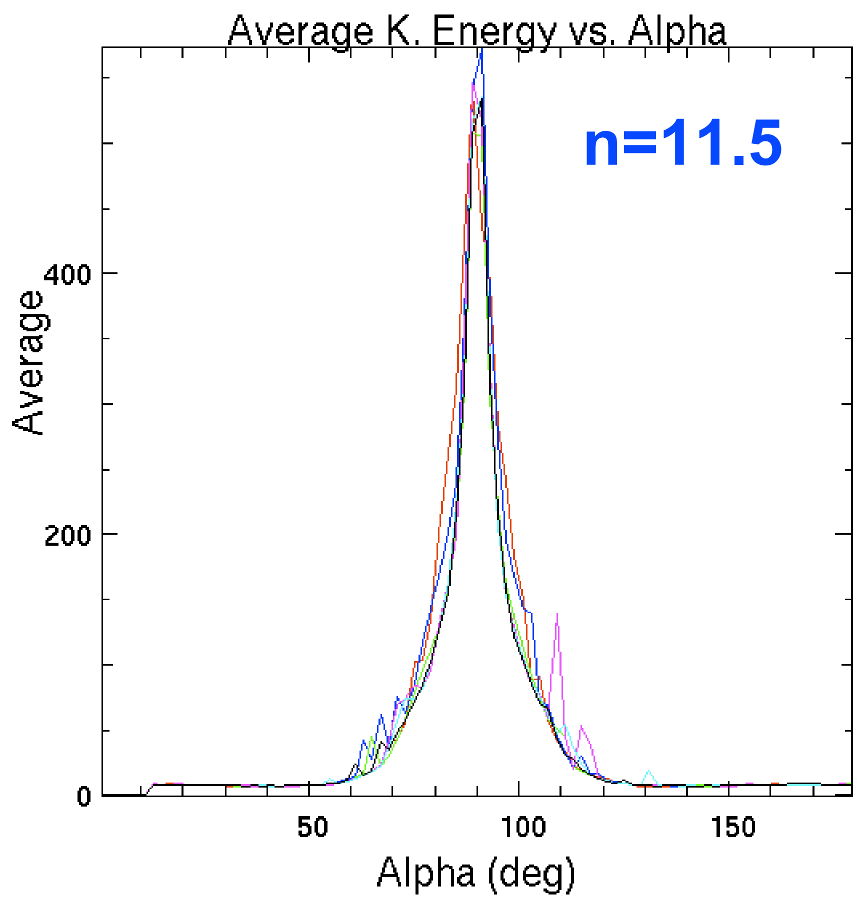
B at a spike



High B

At resonance, electrons over a much bigger area have 100 - 200 eV





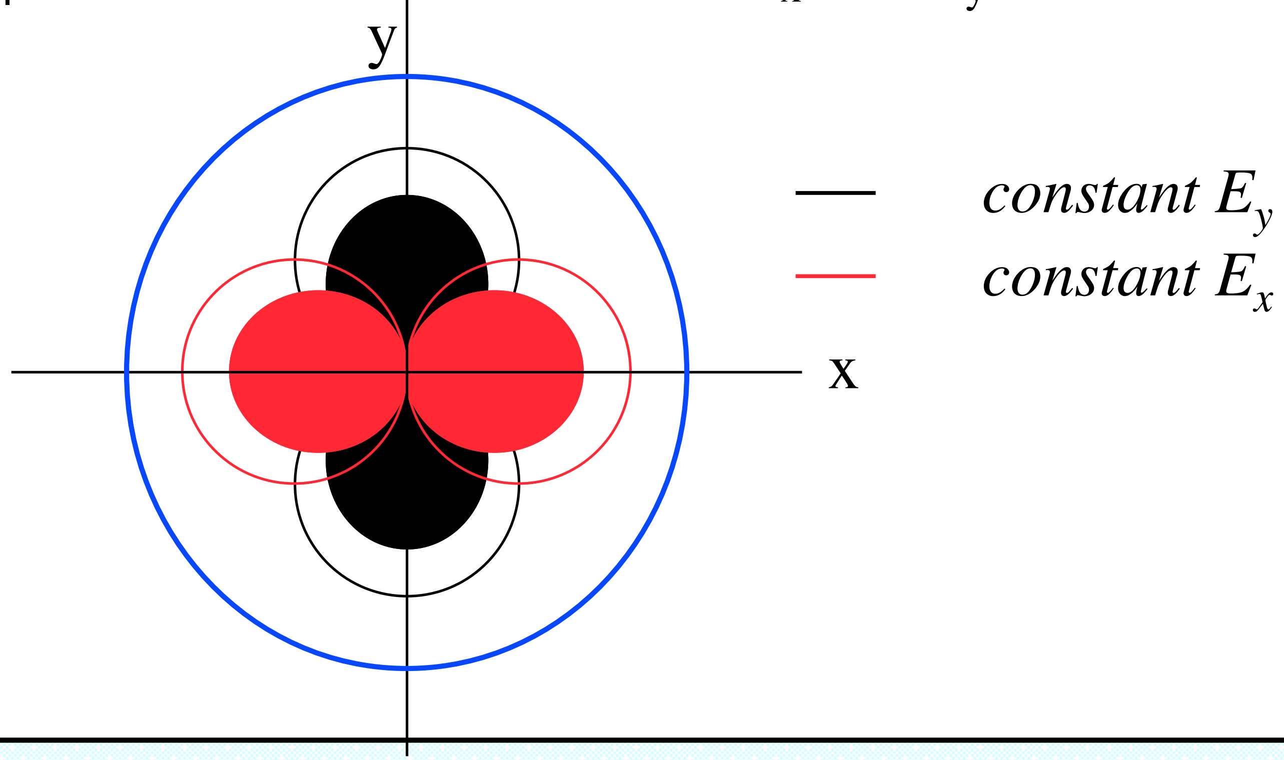
At resonance there is an additional method of adding energy-- the beam E_x can be effective, not just E_y. This changes the locations where electrons feel the greatest effect from the beam.

At resonance both the x and y beam kicks are important to increasing the energy

In what part of the chamber is the beam force most effective?

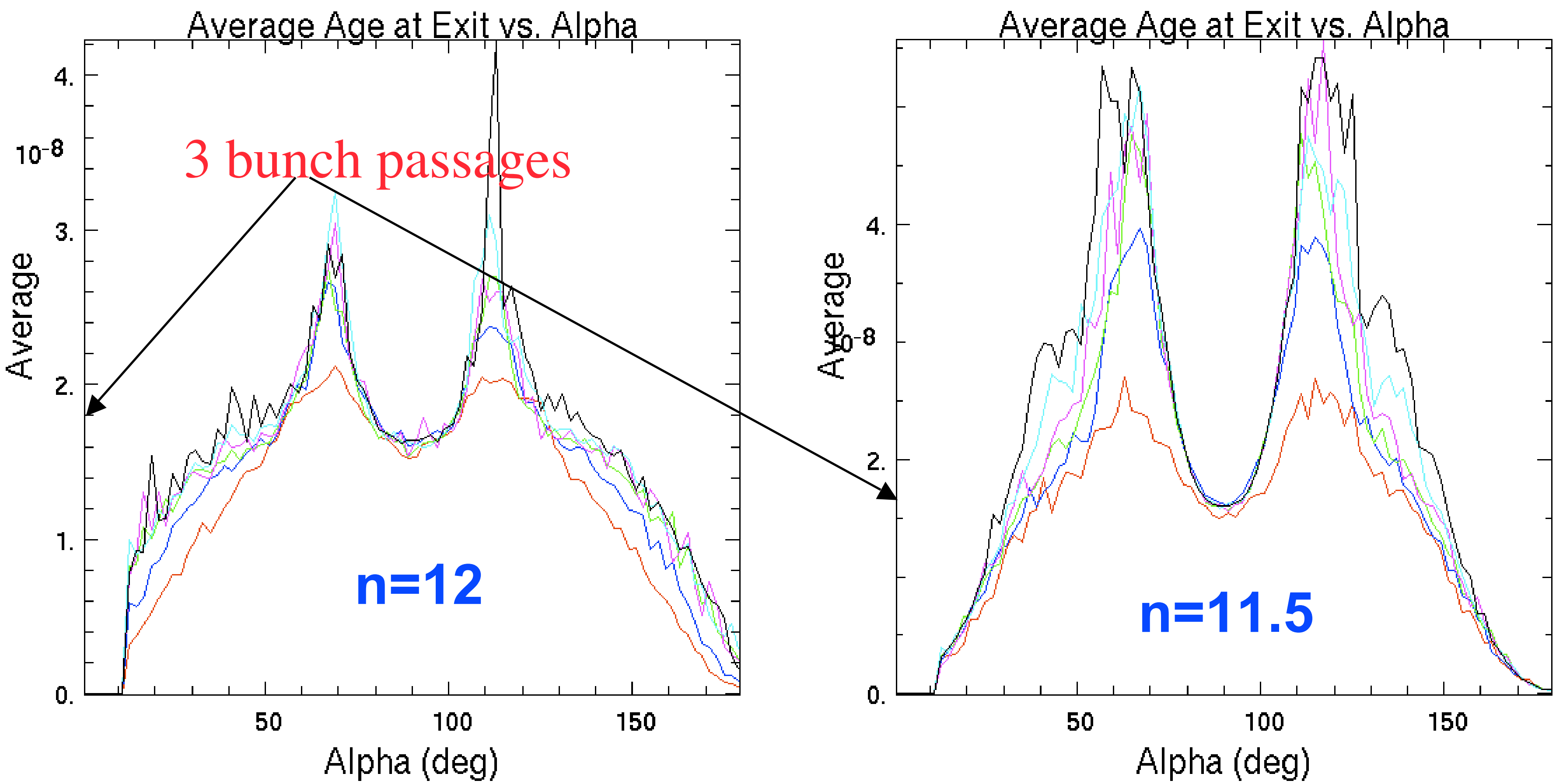
Assume $r >> \sigma_x$, $r >> \sigma_y$.

Then $|E| \propto 1/r$. Contours of constant E_x and E_y are:



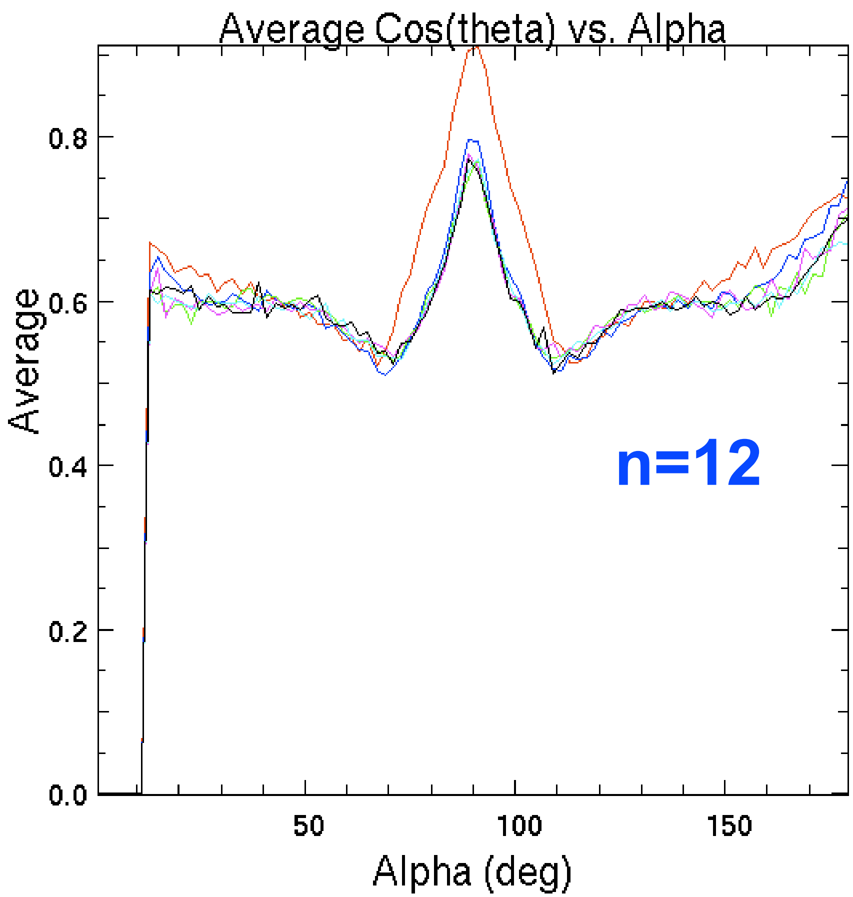
So at resonance, more electrons can pick up the energy needed to make secondaries.

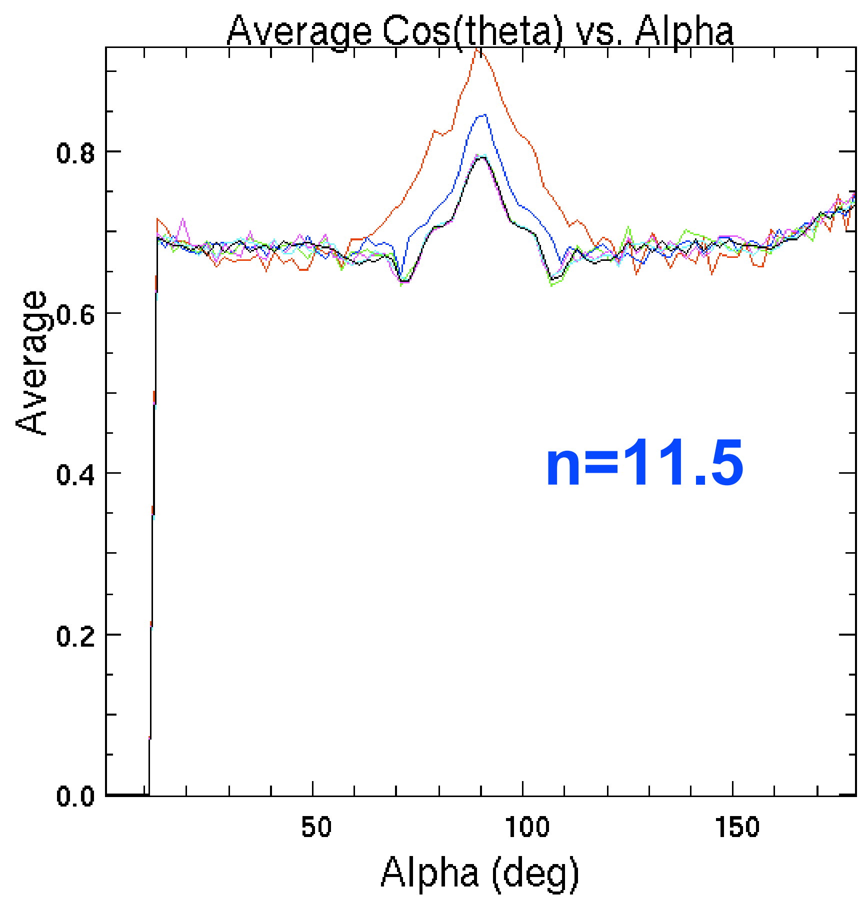
Max energies at wall not very different, probably because electrons exit early for resonant case



- Early exit is consistent with single particle tracking results.
- Though a few electrons with energies up to 30 keV occur in the POSINST simulations, almost all electrons are non-relativistic-- they leave before they attain the very high energies.

The increase at resonance in perpendicular energy decreases cos(θ), as predicted.



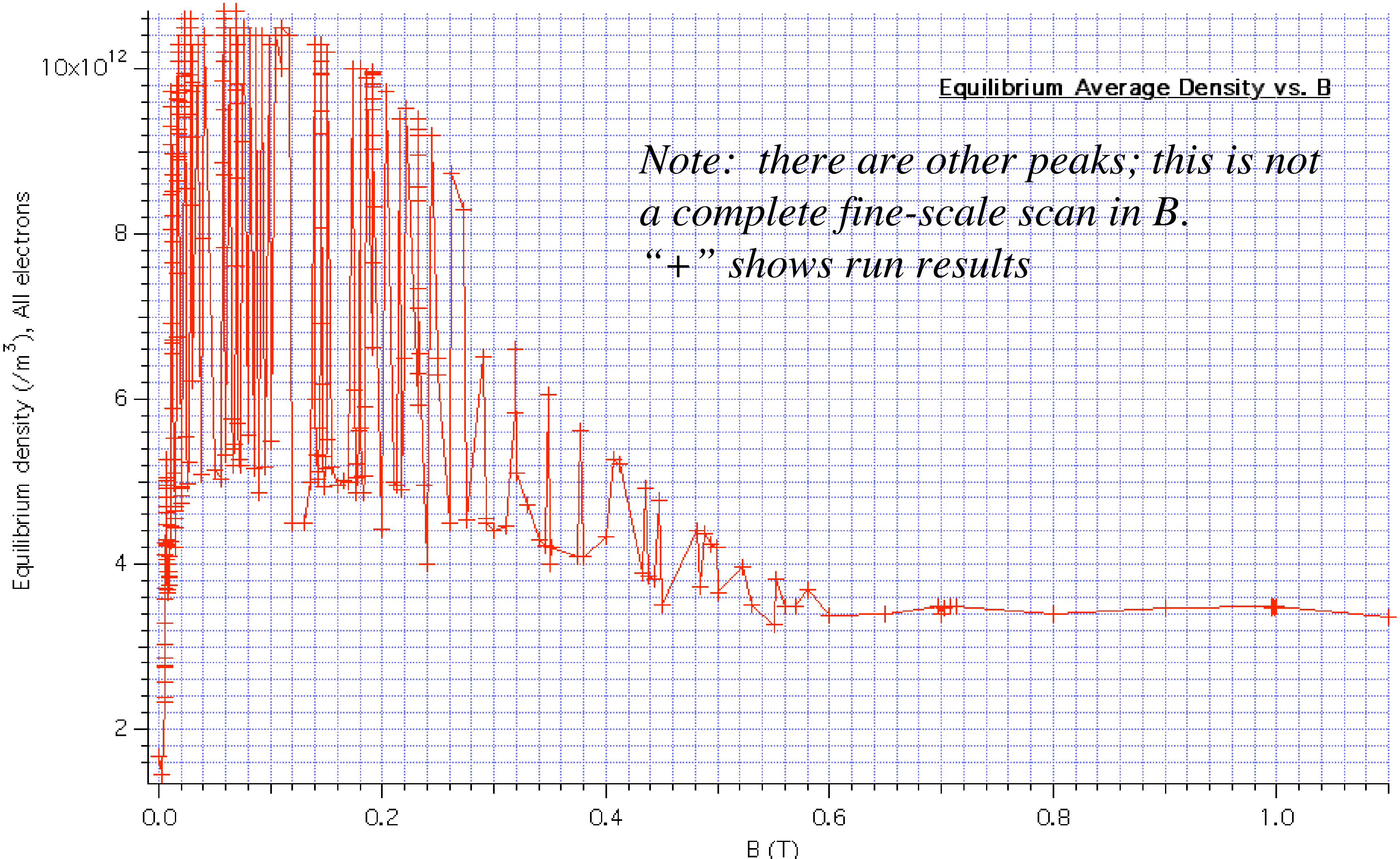


Decreasing the cosine from 0.7 to 0.6 comes from an increase in perpendicular momentum of 30%, assuming $v_{||}$ unchanged.

Why do resonance effects disappear at high B?

Peaks Disappear as B Increases

Equilibrium Average Density vs. B



If the bunch is too long or B too high, the electron moves during the beam passage

Cyclotron period, $\tau_c \propto 1/B$. At high B, $\tau_c < l_b/c$

If during the time the bunch passes the electron moves through a lot of its cyclotron cycle, then the horizontal beam kick averages over cyclotron period, and the concept of the resonance fails*. The peaks drop off in amplitude when

(Cyclotron Period) / (Time for bunch to pass) ≤ 1

or

$$\boxed{B \geq 2\pi \frac{m_0 c}{q l_b},}$$

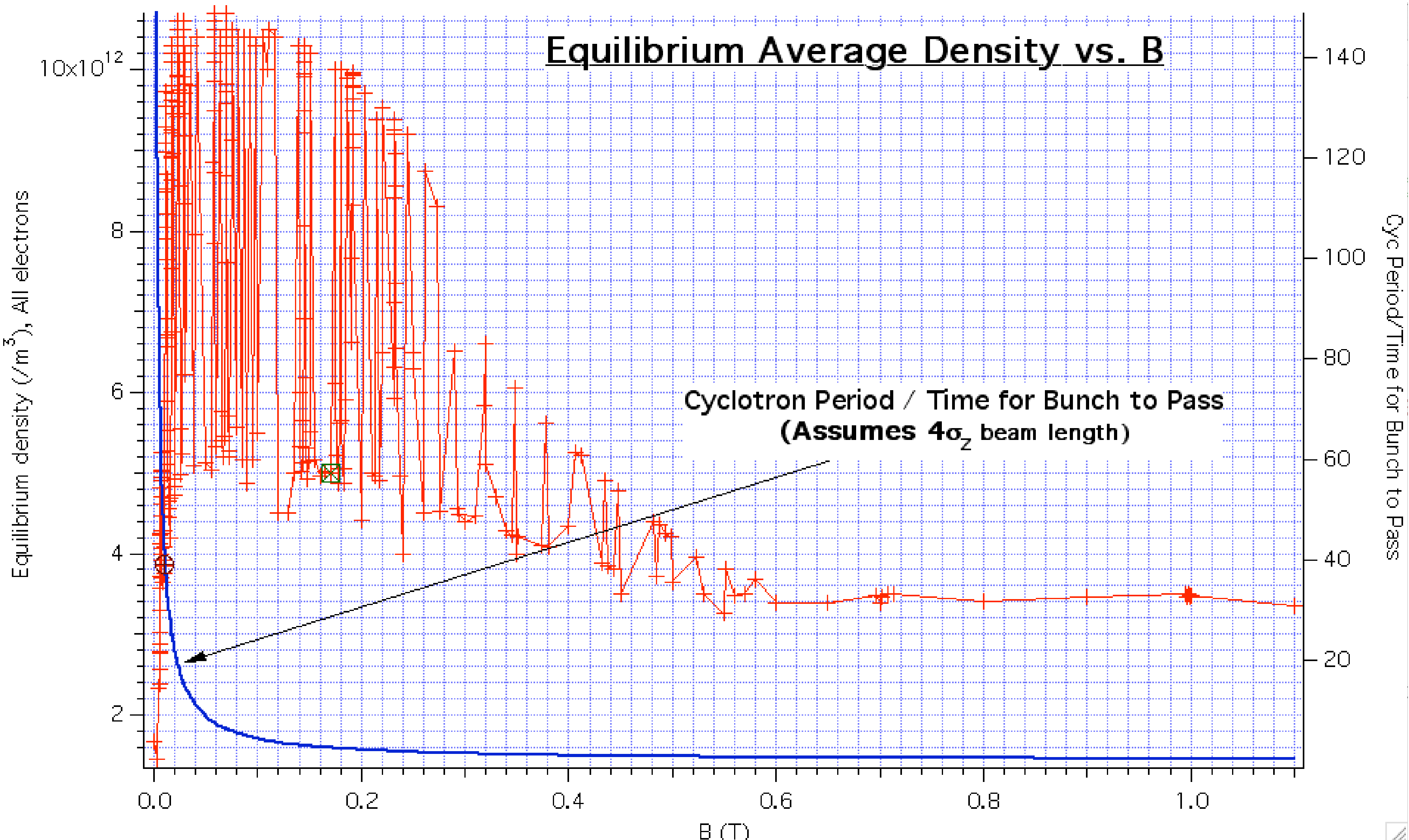
l_b=bunch length

This probably is the reason that the resonance was not noted before--calculations were done for longer bunches and higher fields.

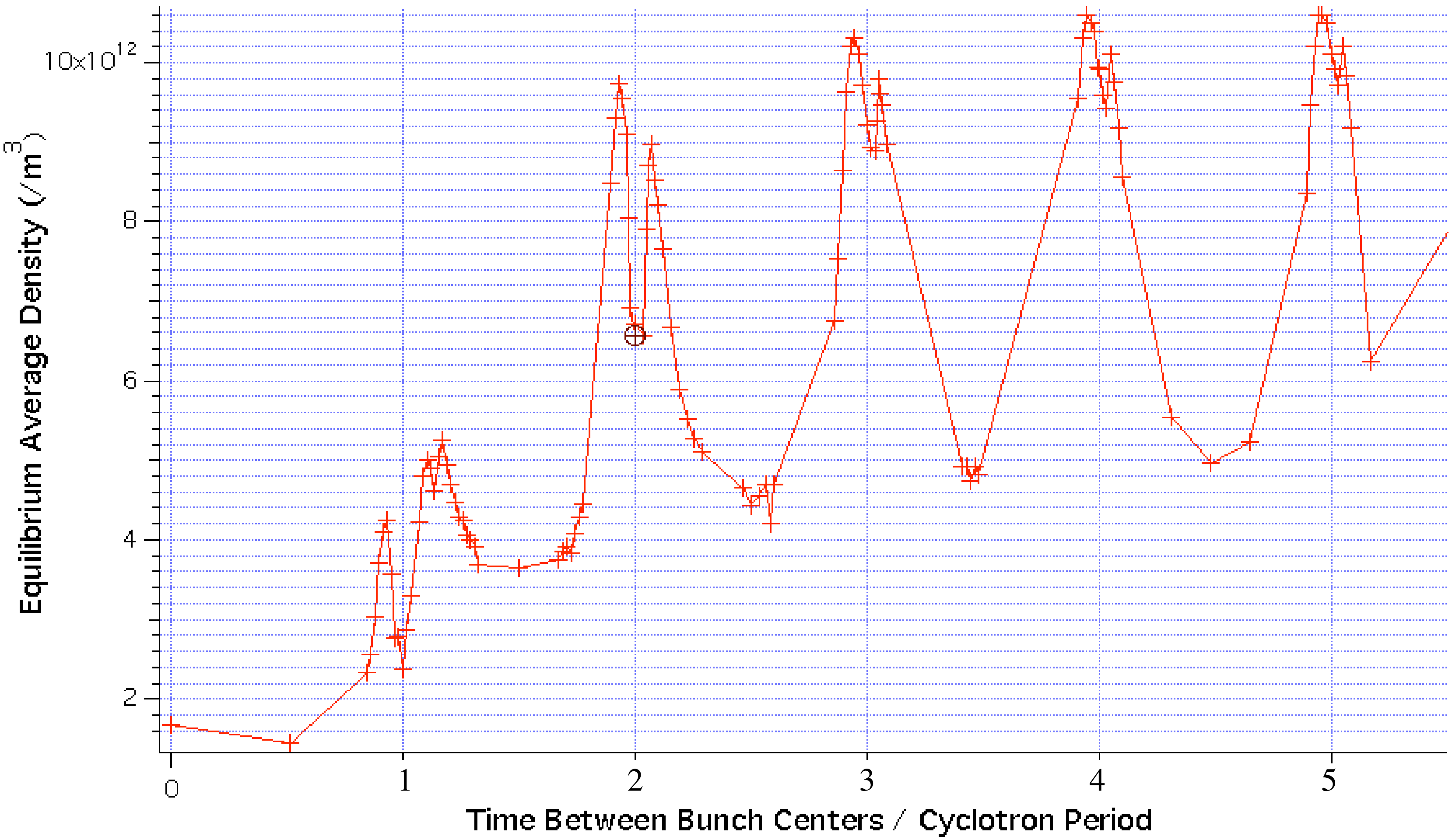
* effect mentioned in different context in Furman and Lambertson, LBNL-41123, 1998

As the time for the bunch to pass nears the cyclotron pd, the peaks disappear

Note: "time for bunch to pass" is a fuzzy number-- depends on choice of bunch length.



Another interesting mystery-- double peaks at low B



Comments on Importance

- This resonant effect produces an increase in the electron cloud density that is not huge (factor of 3), but it is periodic with the wiggler periodicity. Therefore it could possibly cause resonant effects on the beam.

- 3D calculations will be very important in showing what effect this resonance has on the electron cloud magnitude in the wiggler, and in dipole fringe fields. In 3D, the ExB drift will send particles to a different z (and B), so electrons will gradually go in and out of resonance. The resonance may affect more particles, but the effect on a given electron may be less??

We will be doing this soon (WARP3D code)

Conclusions

1. When the bunch period is an integral multiple of the cyclotron period, a resonance occurs. If the electrons stay in the system long enough, their $v_\perp$ increases until the relativistic mass increase detunes them from resonance.
2. In the real system as simulated, most electrons strike the wall after a few bunch passages, but the resonance causes a significant change in $v_\perp$ and in the cloud density.
3. When the time for the bunch to pass is comparable to the cyclotron period (long bunches or high B) the effect averages over the cyclotron oscillation and washes out-- no increase in density.
4. The effect is periodic in z if B is, and could lead to a resonant effect on the beam. But 3D study is needed to confirm or deny.
5. Experimental measurements are needed! - CESR-TA, maybe PEP-II.

This just in (last night) from SLAC ...

Email from Mauro Pivi last night (2-13-08):

Hi Christine!

Very good news! We did the tests yesterday in the chicane and we *clearly* saw the resonances!!